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Heavy quark "Energy loss" and "Flow" in a QCD matter at RHIC

STRANGENESS IN QUARK MATTER

24 - 29 June 2007

Levoča, Slovakia

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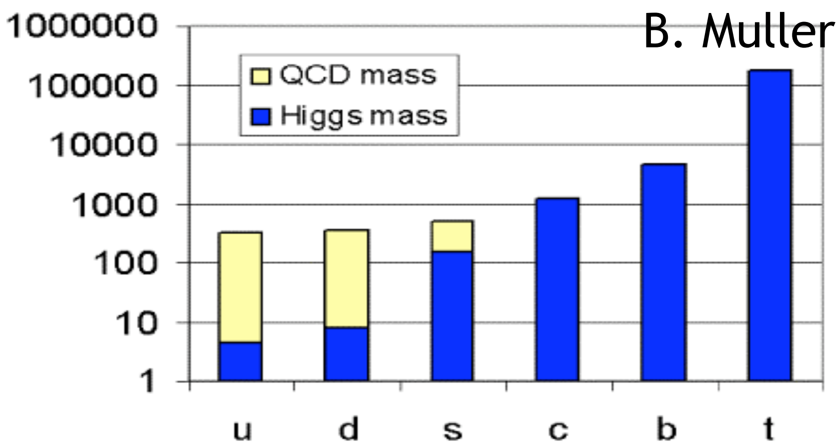
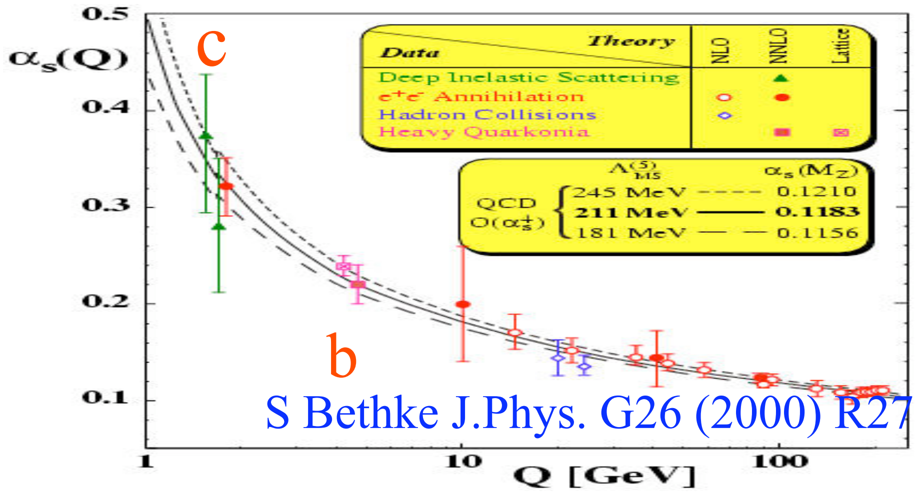
Motivation (I)

Why do we measure heavy quarks (charm/bottom)?

- **In p+p collisions:**
  - **Important test of pQCD. Can pQCD predict charm production(LO, NLO)?**
  - **Base line analysis for d+Au and Au+Au**
- **In d+Au collisions:**
  - **Study of "cold" nuclear matter effect (Gluon Saturation/CGC,[shadowing] , Cronin effect)**
- **In A+A collisions:**
  - **Medium modification effects (energy loss, collective flow)**
  - **Important baseline of J/ψ**

Why Heavy Quarks ?





- Heavy quarks (charm and beauty) - produced early in the collision. Live long enough to sample the plasma
- Intrinsic large mass scale allows precise calculations

What can we look in order to find out the characteristics or properties of the medium(QGP)

☹ **Yields of charm and beauty pairs compared to first principle lattice simulations determine the energy density and temperature**
→ J/Ψ suppression

☺ **Comparison between light and heavy quark suppression distinguishes between theoretical models of energy loss in the QGP**
➔ Charm vs Light quark energy loss (Jet-Quenching)

☺ **Mass dependence of diffusion of heavy quarks determines plasma properties, e.g. viscosity and conductivity ➔ Charm flow**

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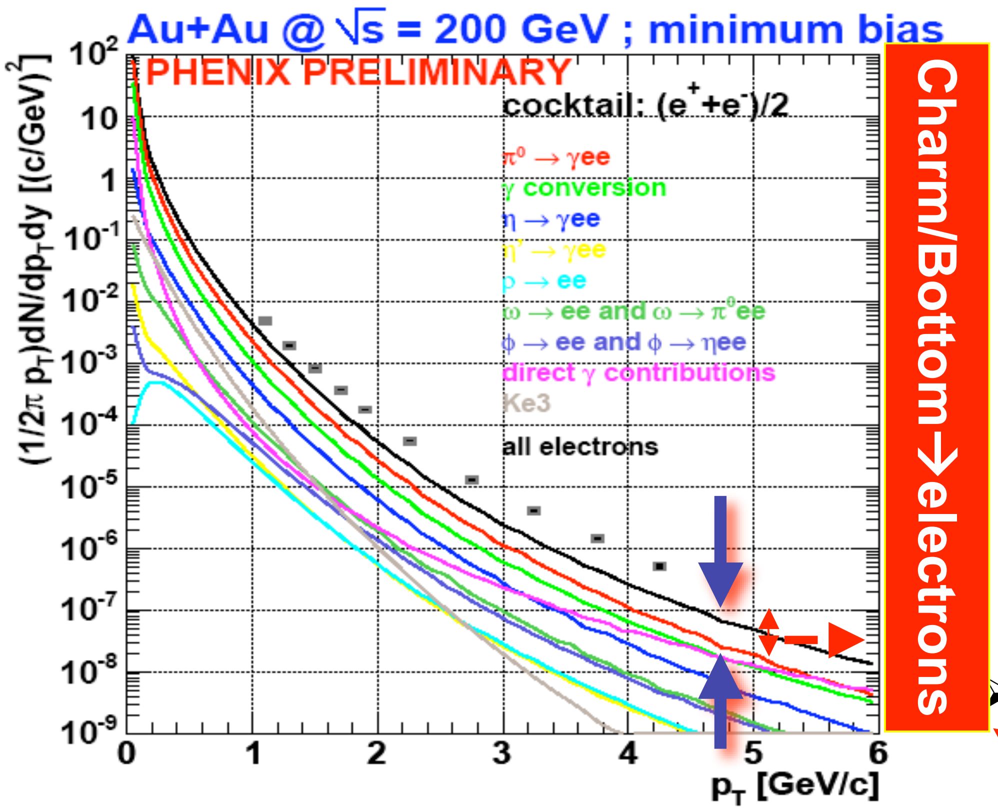
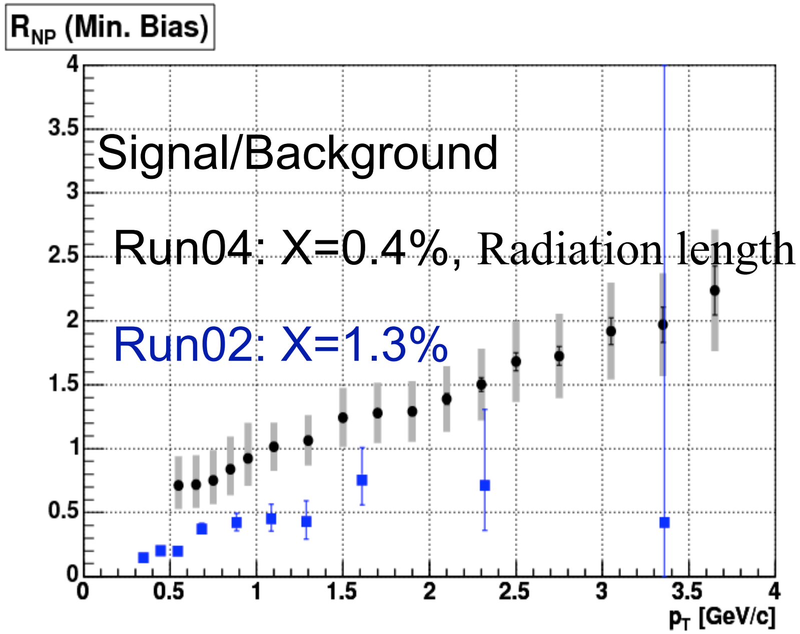
Analysis





S/B > 1 for p_T > 1 GeV/c

We use two different methods to determine the non-photonic electron contribution (Inclusive = photonic + non-photonic)

- Cocktail subtraction – calculation of "photonic" electron background from all known sources
- Converter subtraction– extraction of "photonic" electron background by special run with additional converter (X = 1.7%)

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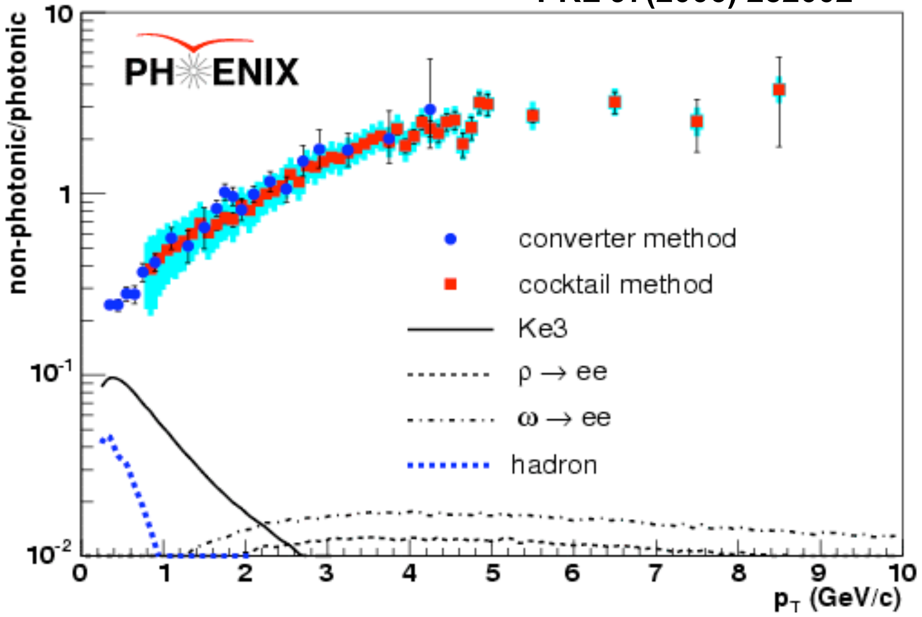
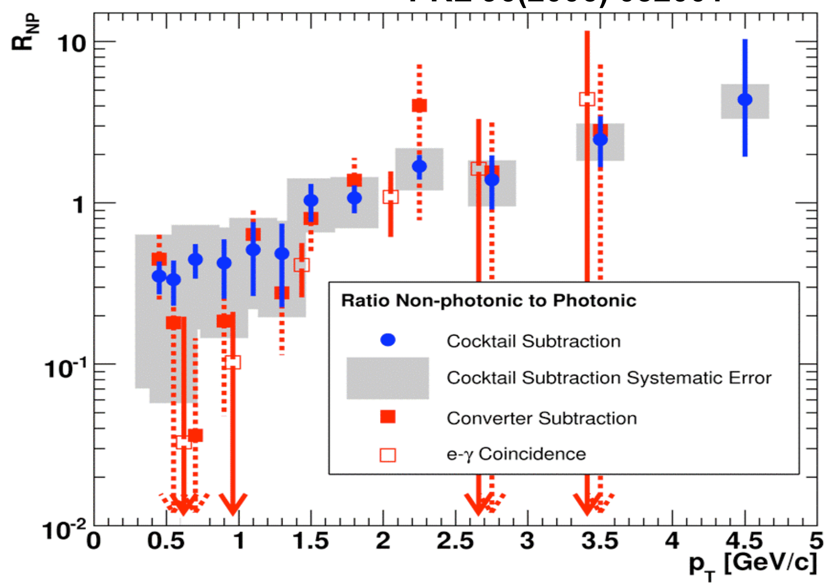
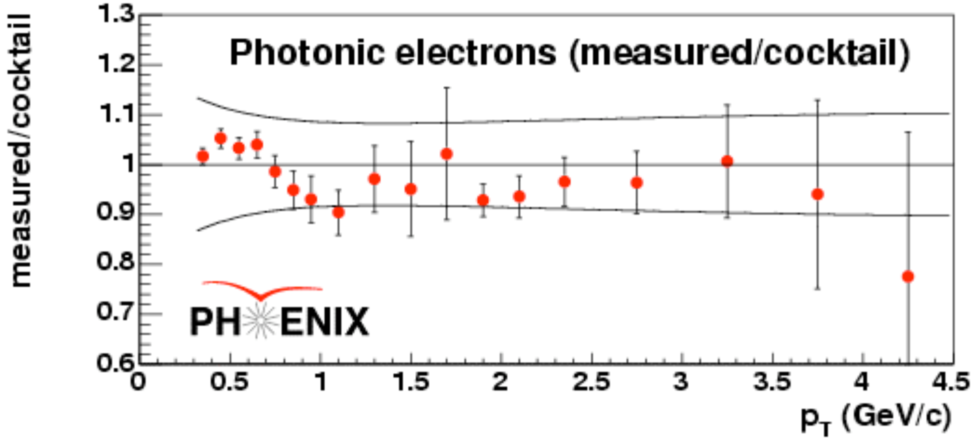
Systematics

PRL 97(2006) 252002



PRL 96(2006) 032001

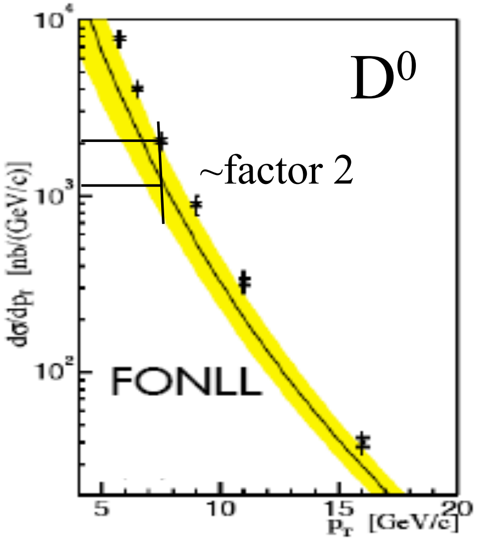




- Cocktail and converter analysis agrees very well
- Low pT : Cocktail
- High pT : Converter
- S/B > 1 for p_T > 1 GeV/c

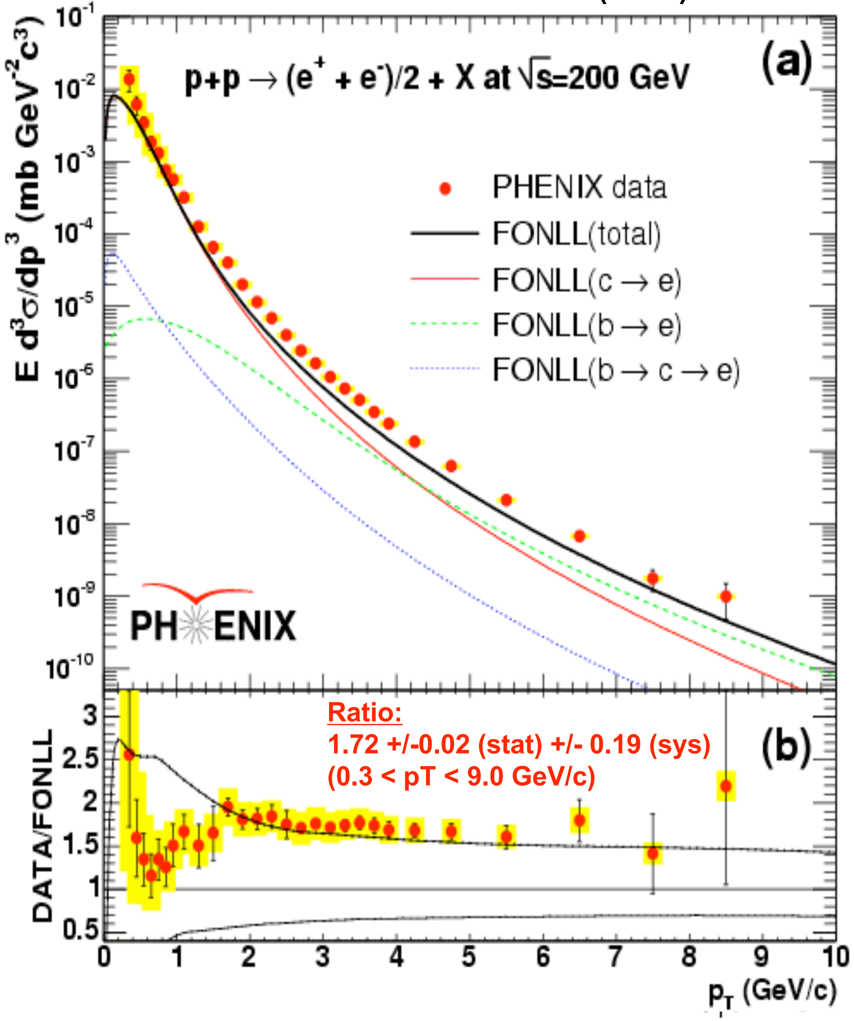
Open Charm in p+p at √s=200 GeV

- σ_{cc}= 567 ± 57(stat) ± 224(sys) μb
- Central value for NLO predictions by M.Cacciari underpredicts the data by 1.7
- pQCD next order corrections usually comparable with error bars on the previous order calculations

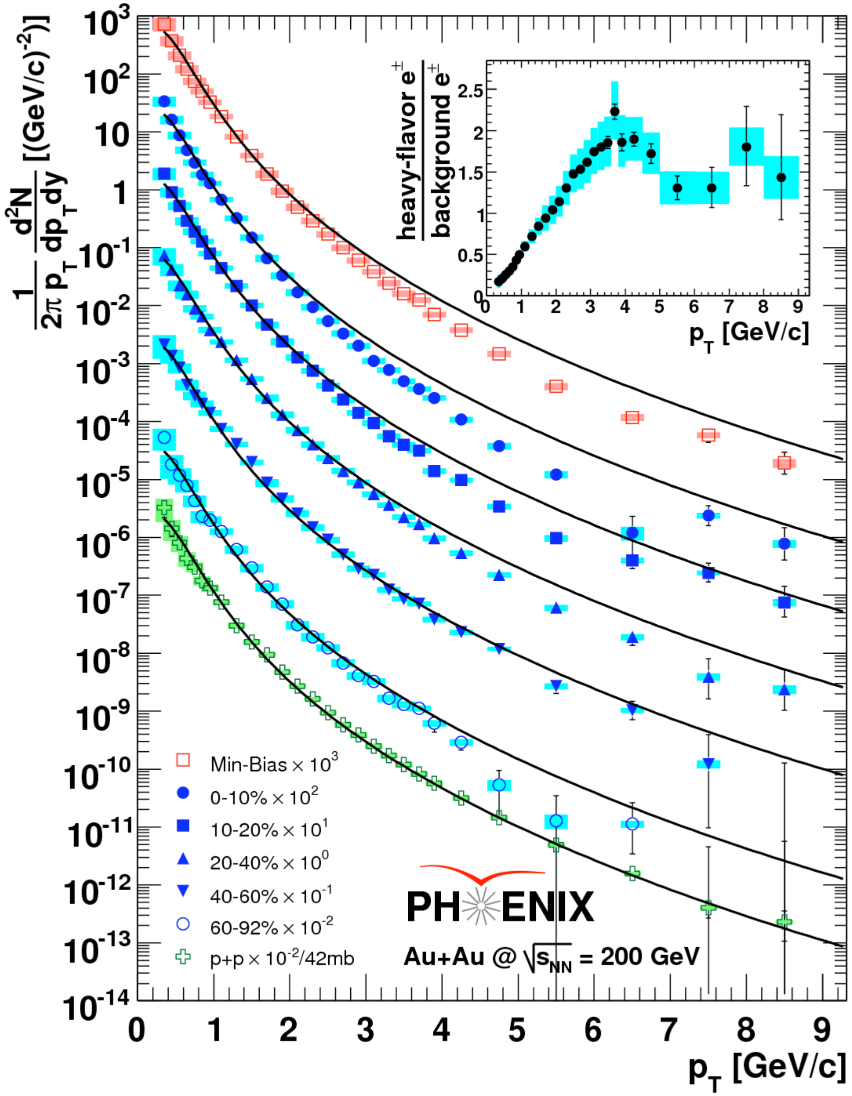


CDF, PRL 91(2003) 241804

PRL 97(2006) 252002



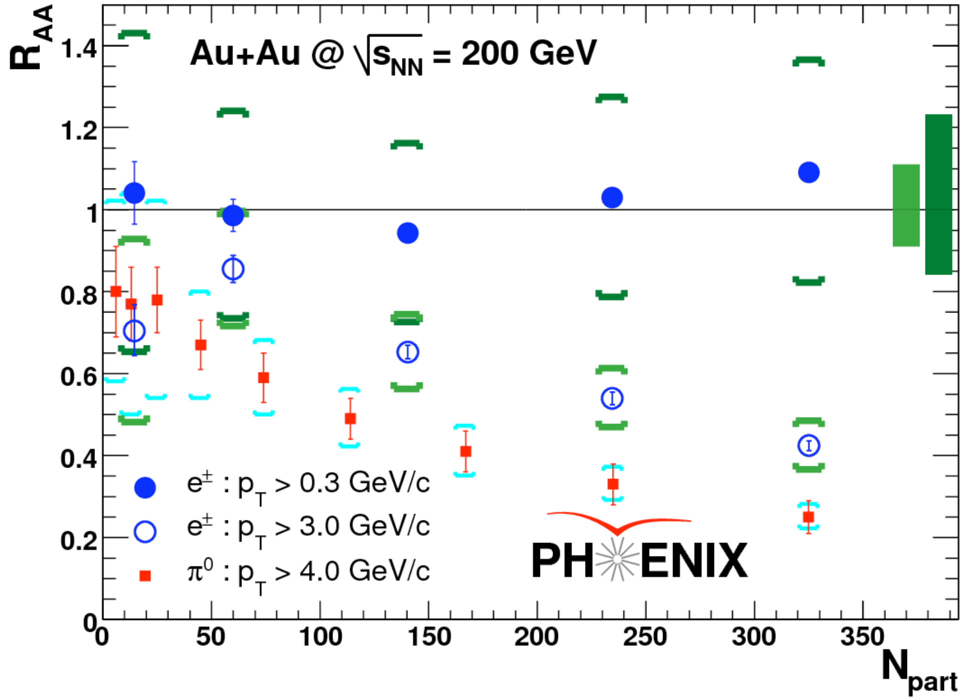
Heavy Flavor in Au+Au 200GeV



PRL. 98, 172301 (2007)

No suppression at low p_T

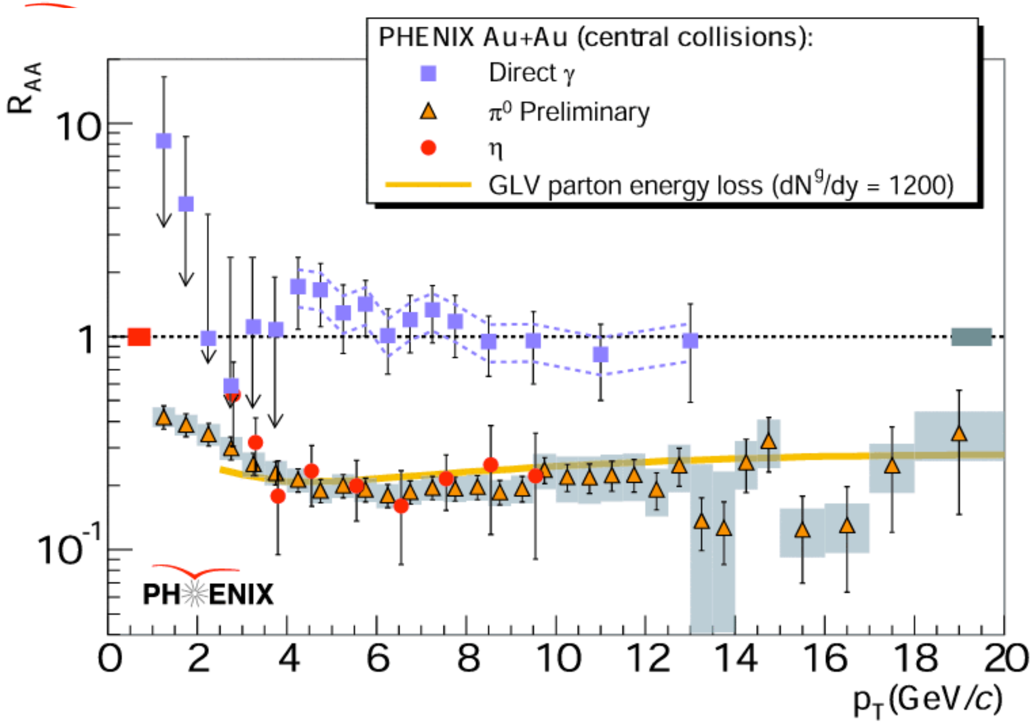
Suppression observed for p_T>3.0 GeV/c, smaller than for light quarks.



Motivation(II)

pQCD jet quenching :

- One of the most celebrated results : issues
  - R_{AA} is of limited value for medium tomography
  - need better constraints on medium modeling : γ-h correlation
- Similar suppression pattern of high-p_T electrons from semi-leptonic *D* and *B* mesons decays as π^0; PRL 91, 172302 (2003) ;
  - how much elastic energy loss is playing a role ? $R_{AA}^{c-quark} \approx R_{AA}^{u,d}$
    - ✓ in addition to radiative energy loss ?
    - ✓ elastic energy loss is well known for π^0
  - α_s is playing a role on energy loss?
    - ✓ how much for radiative and elastic energy loss ?
      ($\Delta E^{radative} \propto \alpha^3_s$, $\Delta E^{elastic} \propto \alpha^2_s$ (ref))
    - ✓ α_s in the medium ? [A.Peshier hep-th/0605294]
  - how modeling on medium is well known?
    - ✓ Medium tomography: *T. Renk, K. Eskola* hep-ph/0610059



$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Measured for:

variety of species

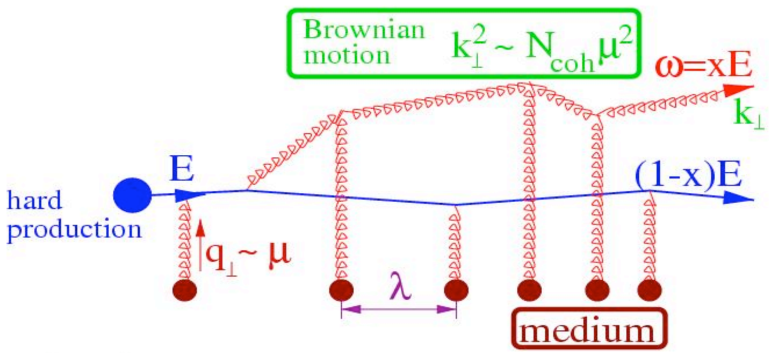
$\pi^0, \pi^\pm, \eta, \gamma_{dir}, p, K_S, \phi, \omega, J/\psi, \Omega\ldots$

and CMS energies

$\sqrt{s}$=17, 22.4, 62.4, 130, 200 GeV/c

Jet quenching - one of the most celebrated results. Light mesons suppressed by factor of 5, direct-γ unsuppressed => FS nature of observed suppression. Data successfully described by pQCD models.

Baier, Schiff and Zakharov, AnnRevNuclPartSci 50, 37 (2000)



Transp. Coef. Scatt. power of QCD med:	Density of scattering centers	Range of color force

$$\hat{q} = \rho \int q^2 dq^2 \frac{d\sigma}{dq^2} \equiv \rho\sigma\langle k_T^2 \rangle = \frac{\mu^2}{\lambda_f}$$

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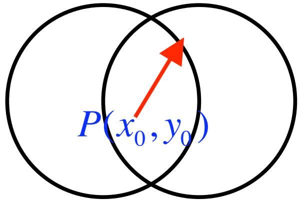
Is R_{AA} sensitive to P(ΔE,E)?

T. Renk, K. Eskola *et al.*

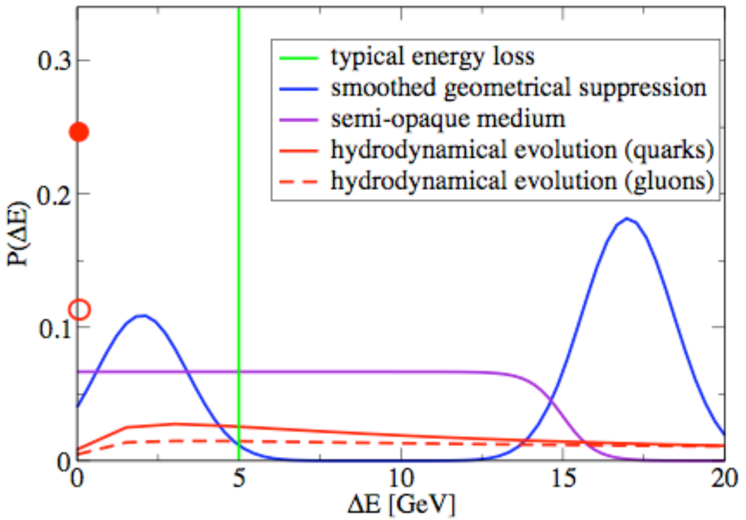
R_{AA} uniquely determined by $p_{had} = p_{part} \otimes \langle P(\Delta E, E) \rangle \otimes D^{vac}_{f \to \pi}(z, \mu_F^2)$

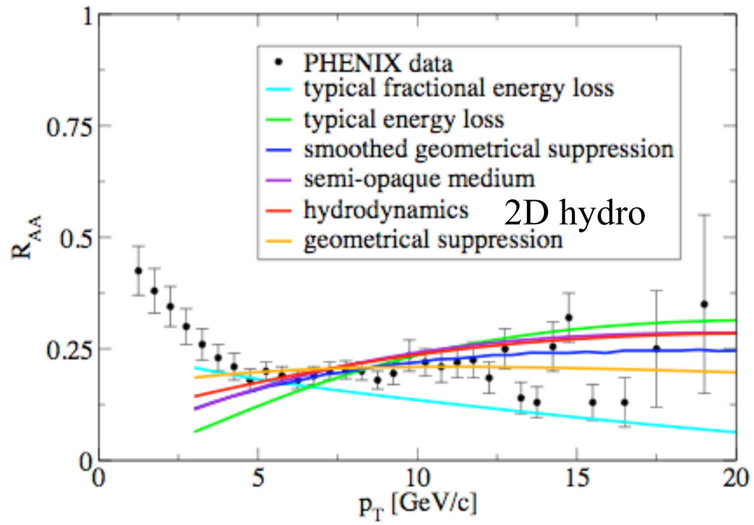
The E-loss probability can be defined:

$$\langle P(\Delta E, E) \rangle_{TAA} = \frac{1}{2\pi} \int_0^{2\pi} d\varphi \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 P(x_0, y_0) P(\Delta E, E)_{path}$$

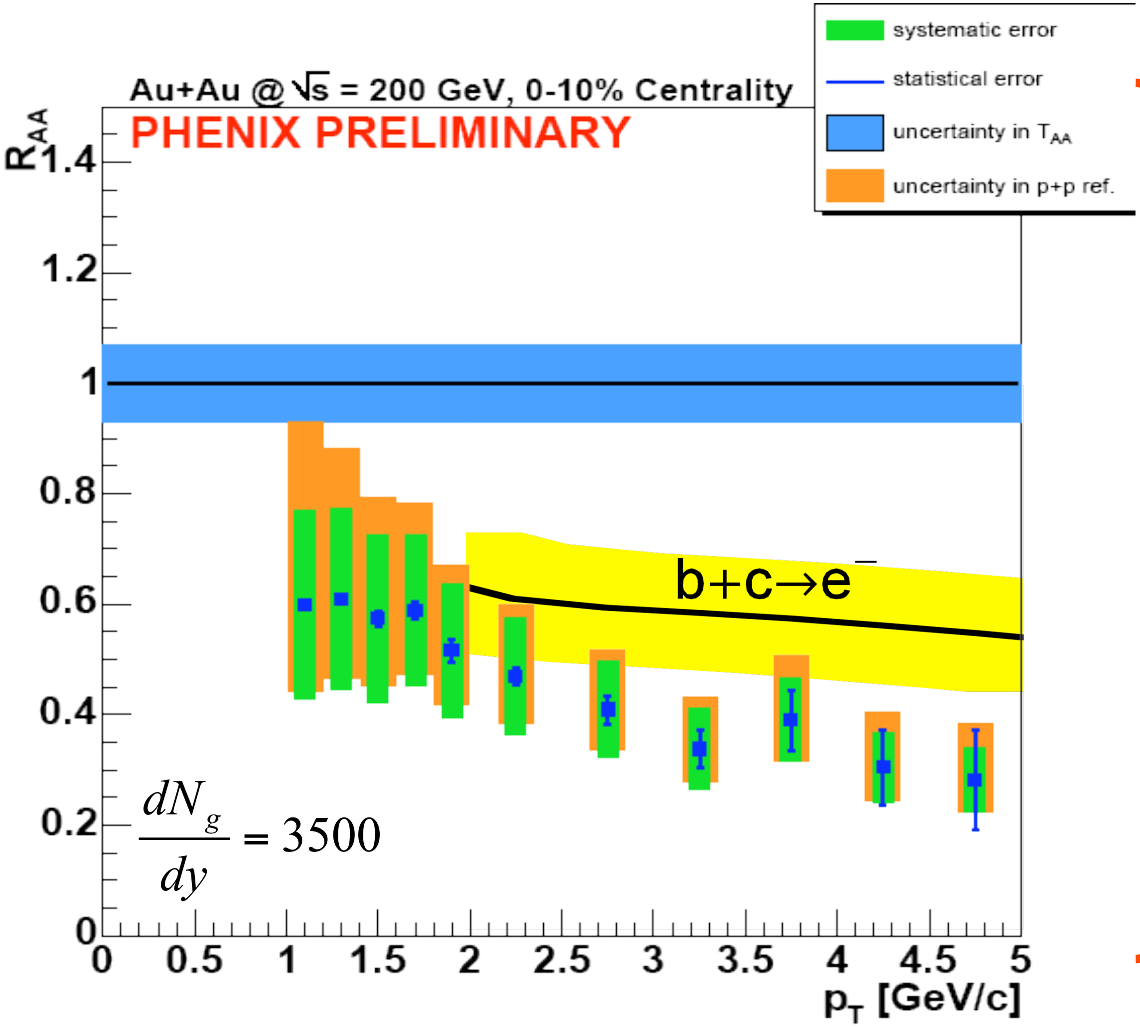


Where hard vertices $P(x_0, y_0) = \frac{[T_A(r_0)]^2}{T_{AA}(0)}$ and $T_A(\vec{r}) = \int dz \rho_A(\vec{r}, z)$





Preliminary Results



dN_g/dy=3500

N. Armesto *et al.*, Phys. Rev. D 71, 054027 (2005)

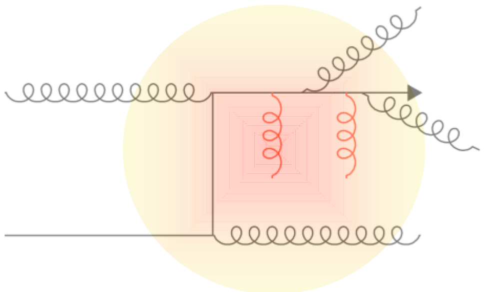
Reasonable agreement, but the dN_g/dy=3500 is not physical!

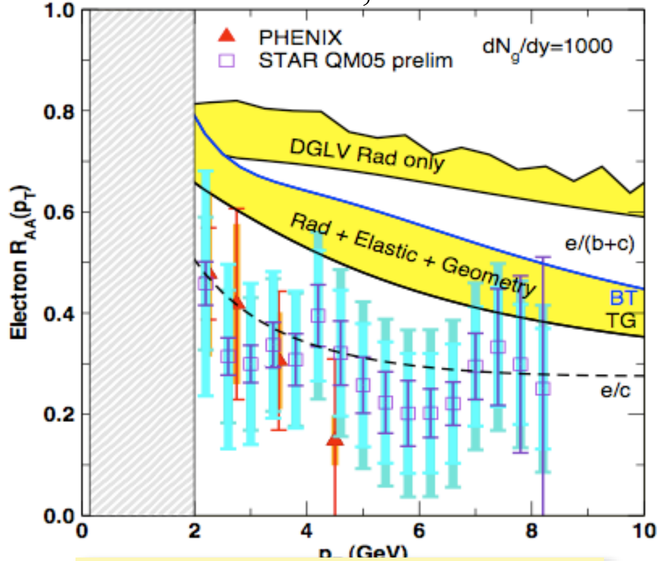
Elastic energy loss

S. Wicks et al., nucl-th/0512076

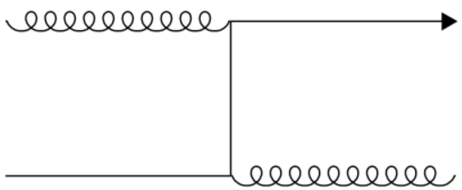
Partonic Energy Loss

Radiative 2→N processes. Final state QCD radiation as in vacuum (p+p coll) - enhanced by QCD medium.





Elastic 2→2 LO processes



8 LO subprocesses

$qq' \to qq' \qquad \frac{4}{9}\frac{s^2+u^2}{t^2}$

$qq \to qq \qquad \frac{4}{9}\left[\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right]$

$q\bar{q} \to q\bar{q}' \qquad \frac{4}{9}\frac{t^2+u^2}{s^2}$

......

Elastic ΔE models predict significant broadening of away-side correlation peak - not seen in the data. Also various models differ significantly in radiative/elastic fraction.

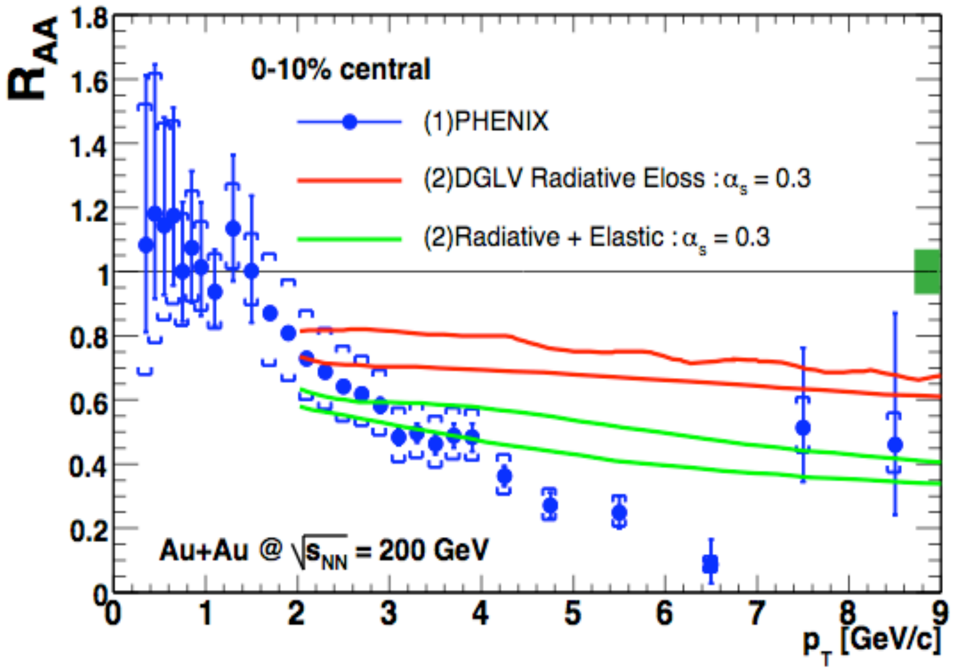
Elastic energy loss

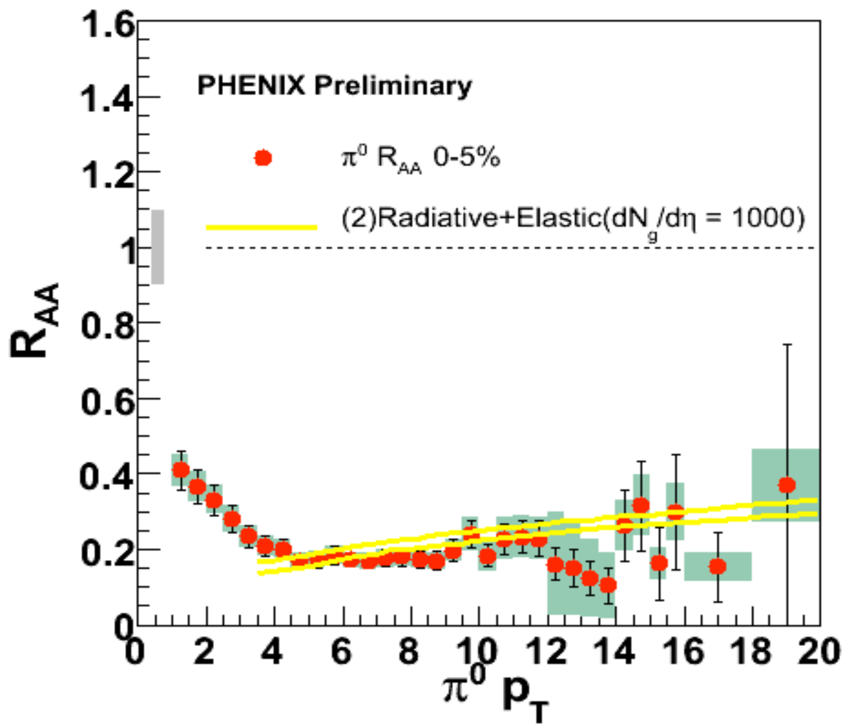
First results indicate that the elastic energy loss may be important
M. G. Mustafa, Phys.Rev.C72:014905,2005

- Electrons

$$\alpha_s = .3$$

- Pions





(1)PHENIX ,PRL. 98, 172301 (2007)

(2) M. G. Mustafa, Phys.Rev.C72:014905,2005

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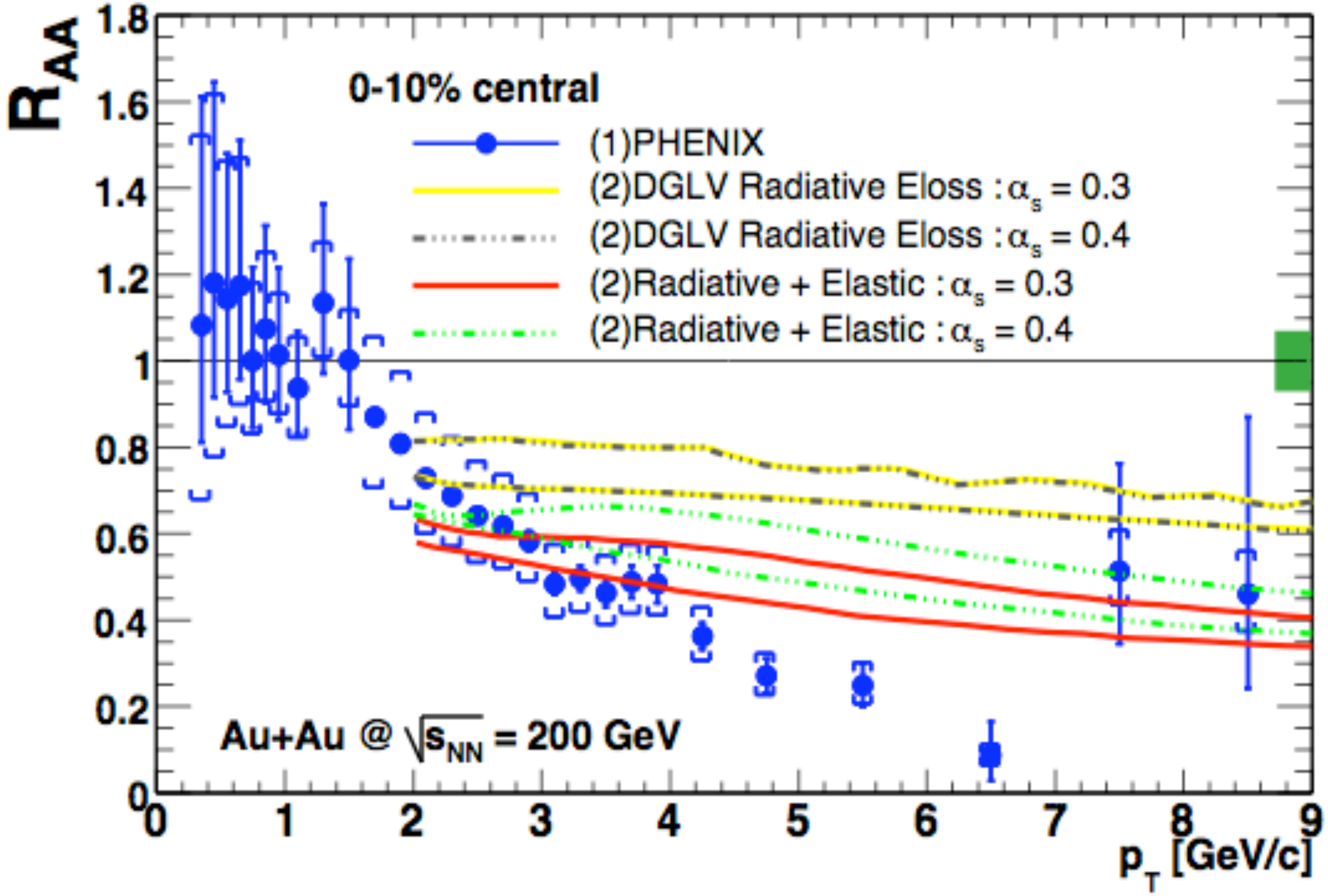
With Different α_s



- α_s is playing a role on energy loss?
  - ✓ how much for radiative and elastic energy loss ?
    ($\Delta E^{radative} \propto \alpha^3_s$, $\Delta E^{elastic} \propto \alpha^2_s$ (?))

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What is α_s in a QGP?

A. Peshier, hep-ph/0605294

- In BJs collisional loss formula
- (adaption of rel. Bethe-Bloch)

$$\frac{dE^{Bj}_{q,g}}{dx} \sim T^2 \alpha_s^{\,2} \ln \frac{ET}{m_D}$$

- What is α_s in a QGP?

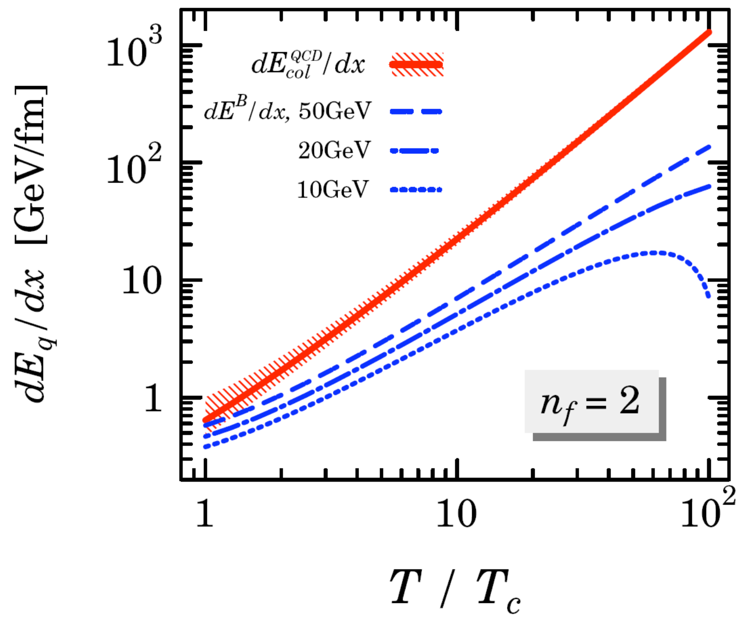
- A fixed parameter?
- Isn't it running ?

•Take running coupling into account

$$\frac{dE^{AP}_{col}}{dx} \sim T^2 \alpha(m_D)$$

- – independent of jet energy
- – for T > 1.5 T_C considerably larger than previous estimates

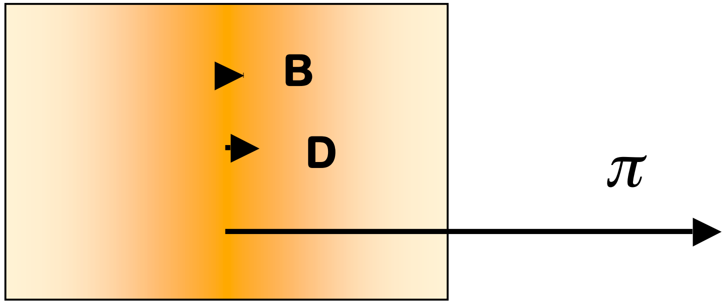
•



Collisional dissociation ?

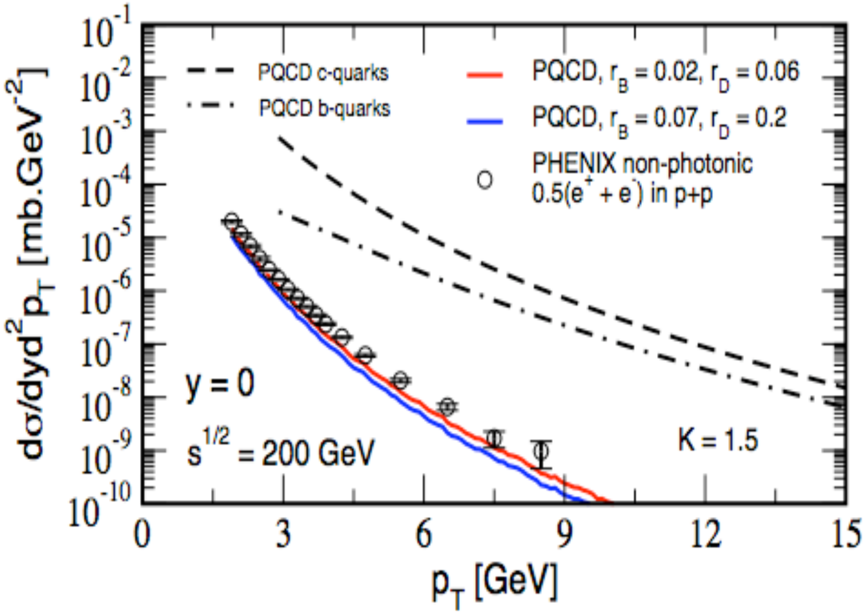
(3)I. Vitev (A.Adil, I.V., hep-ph/0611109), Phys Lett B649 139-146 2007

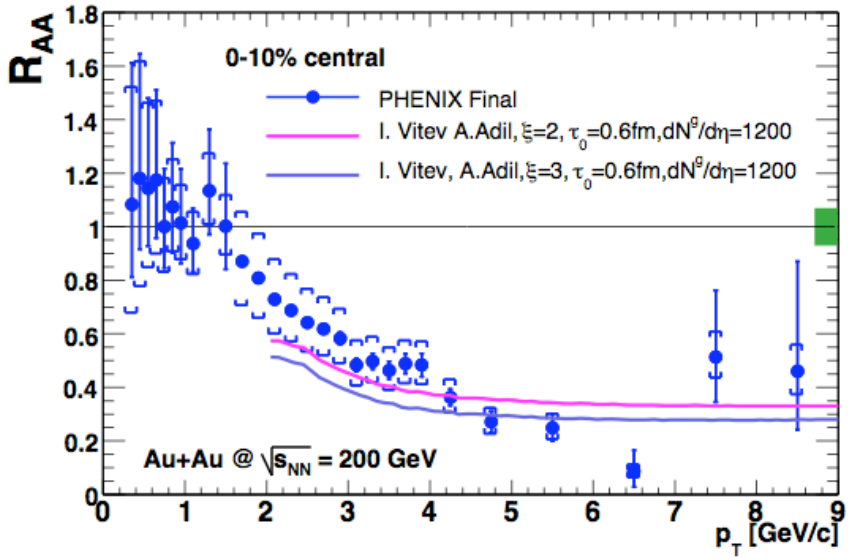
QGP extent



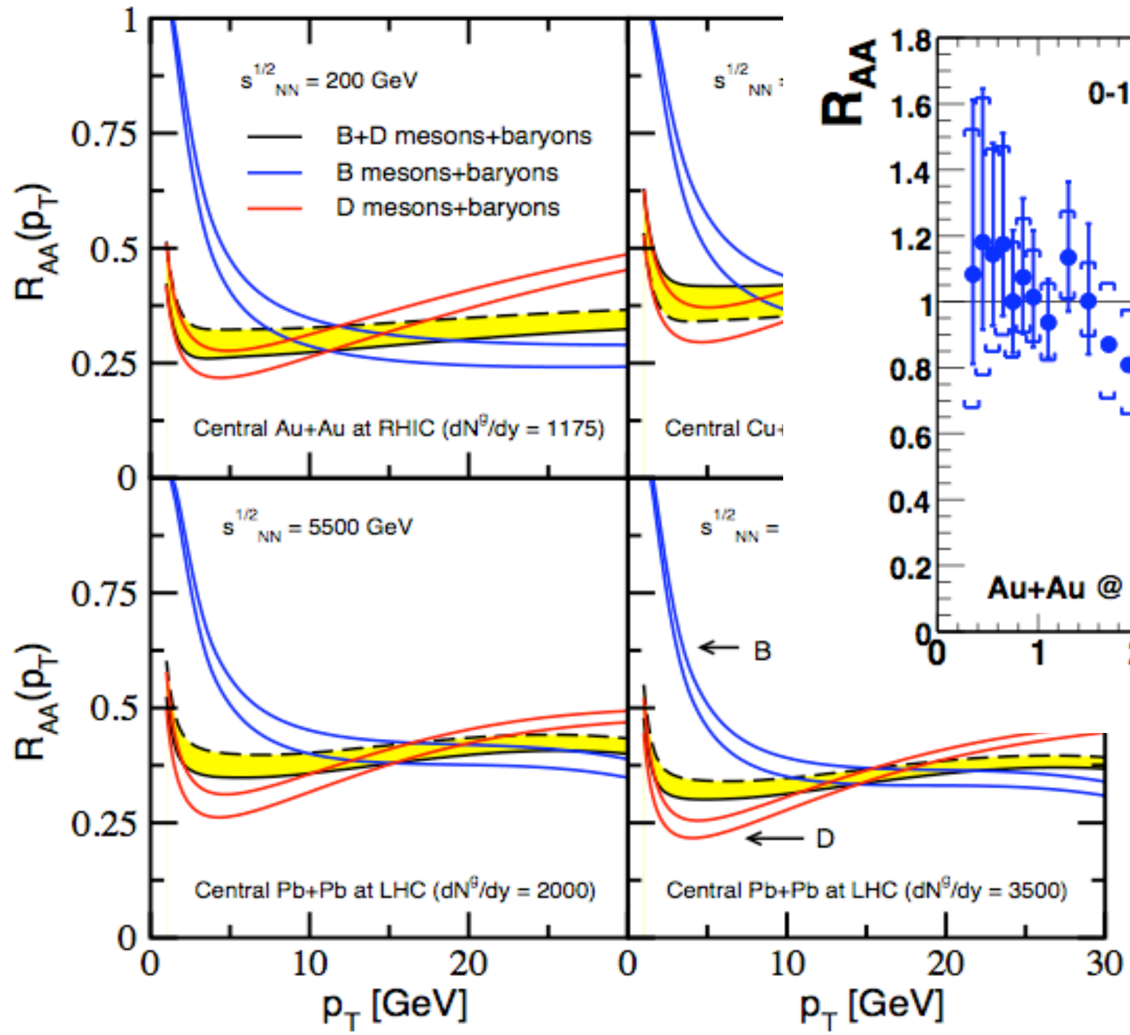
$$\tau_{\text{form}}(p_T = 10\ GeV) \quad \begin{array}{ccc} \pi & D & B \\ \hline \textbf{25 fm} & \textbf{1.6 fm} & \textbf{0.4 fm} \end{array}$$

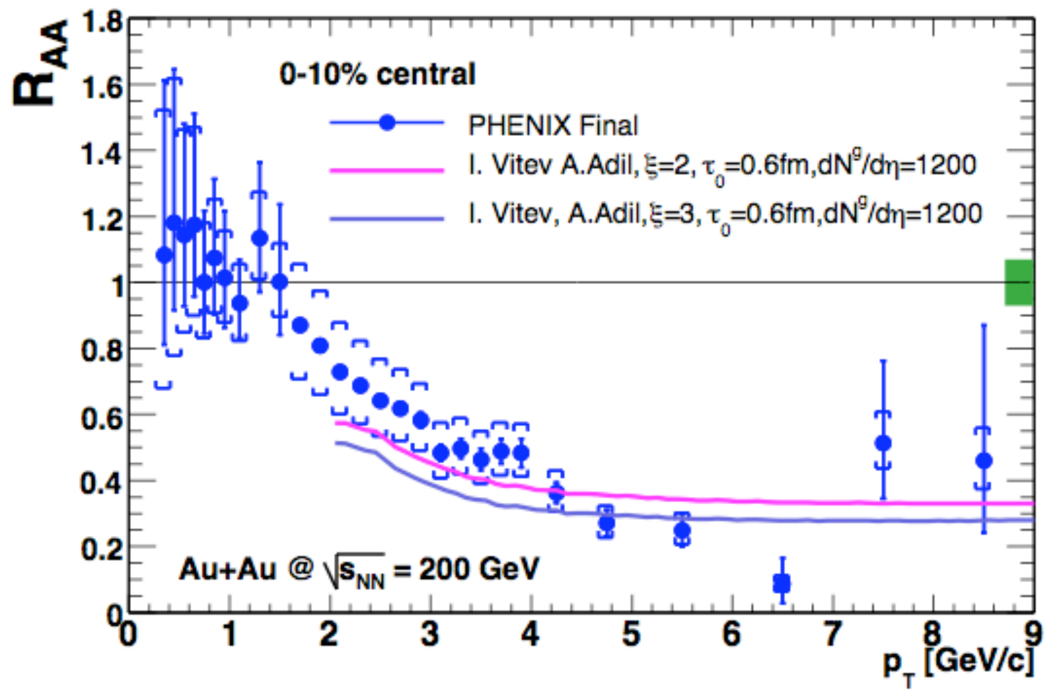
- Fragmentation and dissociation of hadrons from heavy quarks inside the QGP





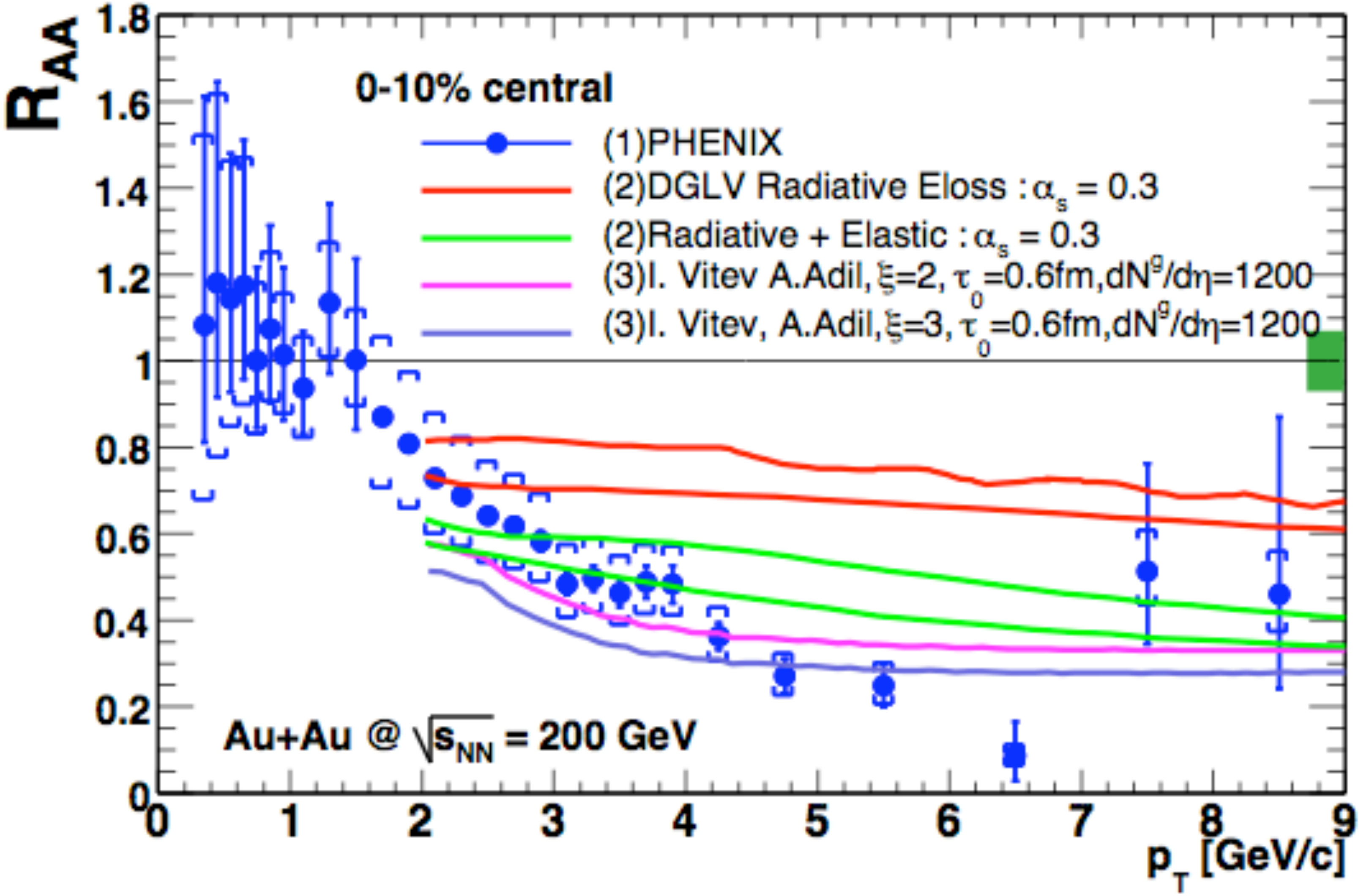
Collisional dissociation ?





Note that R_{AA}(D) is comparable to R_{AA}(B) in this calculation or larger > 10GeV

Energy Loss is being understood ?



Non-photonic electron v_2 measurement

Shingo QM06

- Non photonic electron v_2 is given as;

$$\begin{cases} \dfrac{dN^{e}}{d\Phi} = \dfrac{dN^{\gamma.e}}{d\Phi} + \dfrac{dN^{non-\gamma.e}}{d\Phi} & (1) \\[2ex] v_2^{non-\gamma.e} = \dfrac{(1+R_{NP})v_2^{e} - v_2^{\gamma.e}}{R_{NP}} & (2) \end{cases}$$

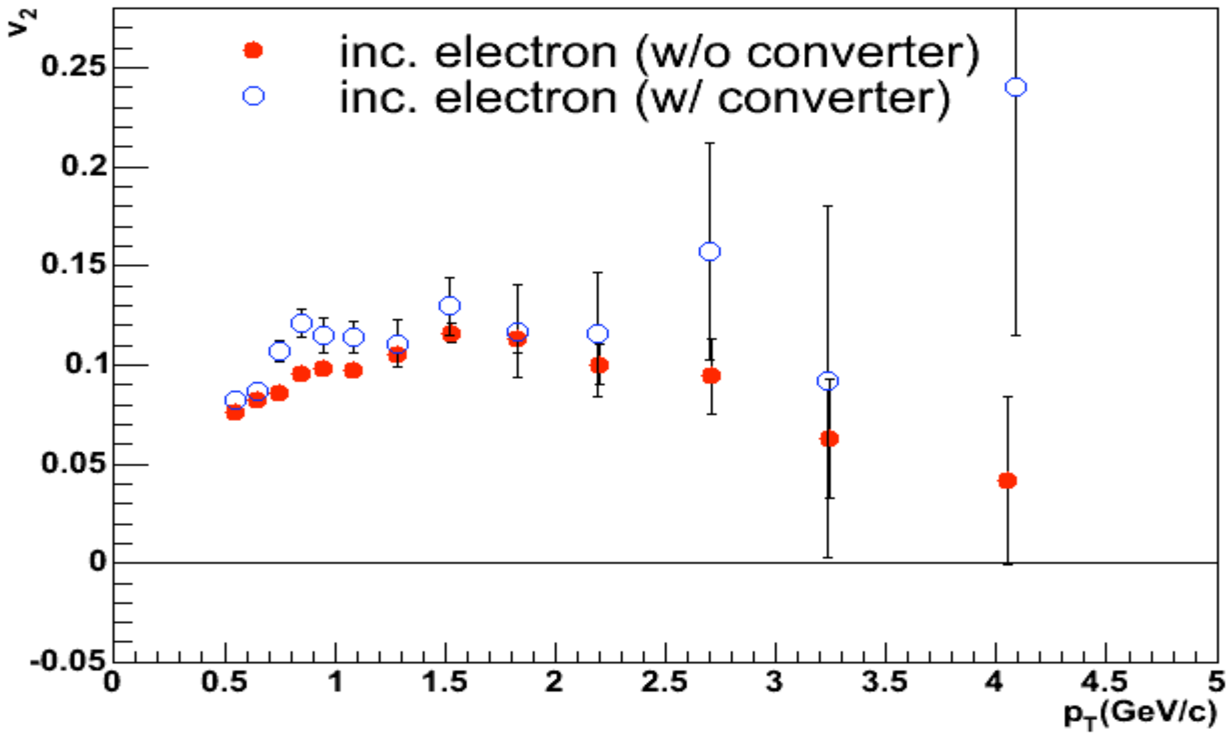
v_2^e ; Inclusive electron v_2
=> Measure

R_{NP} = (Non-γ e) / (γ e)
=> Measure

$v_2^{\gamma.e}$; Photonic electron v_2
⇒ Cocktail method (simulation) stat. advantage
⇒ Converter method (experimentally)

Inclusive electron v_2

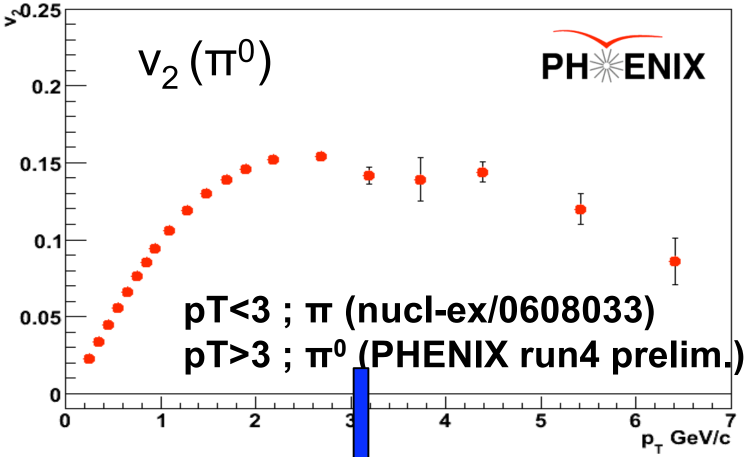
Shingo QM06

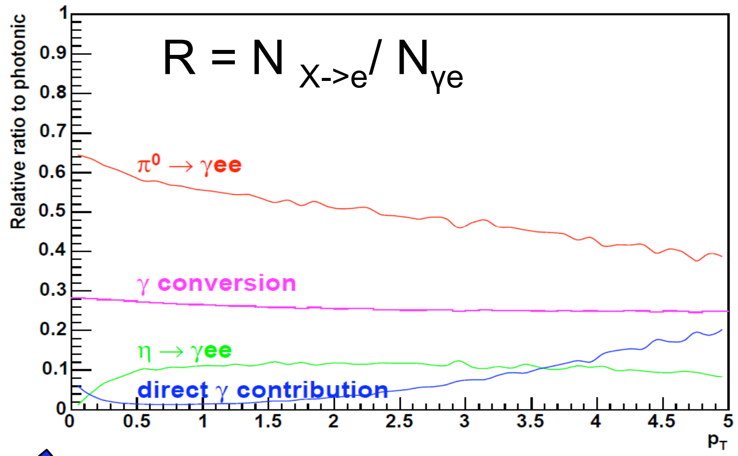


- inclusive electron v_2 measured w.r.t reaction plane
- converter --- increase photonic electron
- photonic & non-photonic e v_2 is different

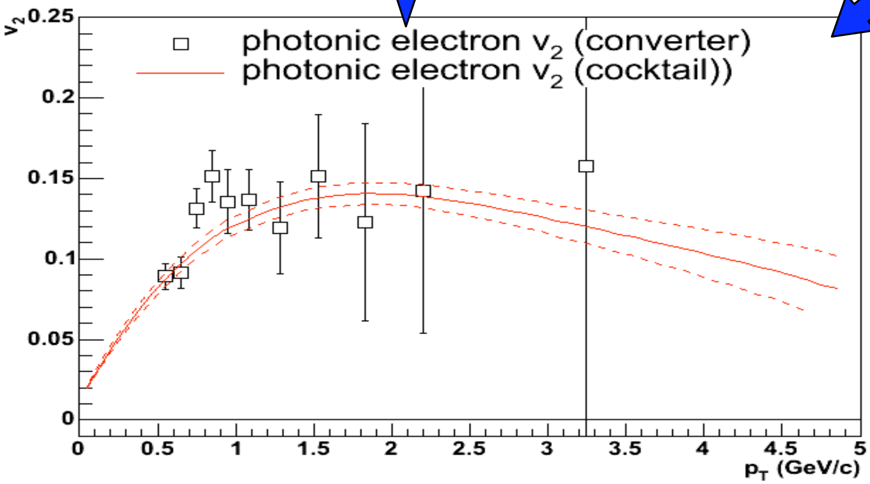
Photonic e v_2 determination

Shingo QM06





decay



- photonic electron v_2
  => cocktail of photonic e v_2

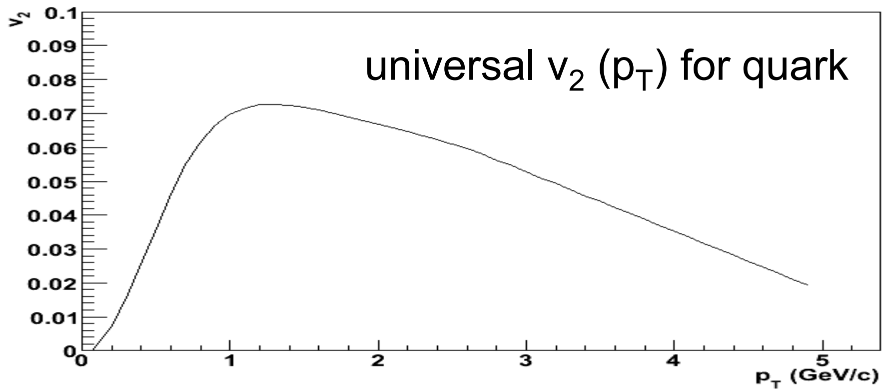
$$v_2^{\gamma.e} = \sum R \times v_2^{decay}$$

- good agreement
  converter method
  (experimentally determined)

Non-zero charm v_2 ? (1)

Shingo QM06

- Apply recombination model
- Assume universal v_2 (p_T) for quark



Shape is determined with measured identified particle v_2

[PRC 68 044901 Zi-wei & Denes]

charm

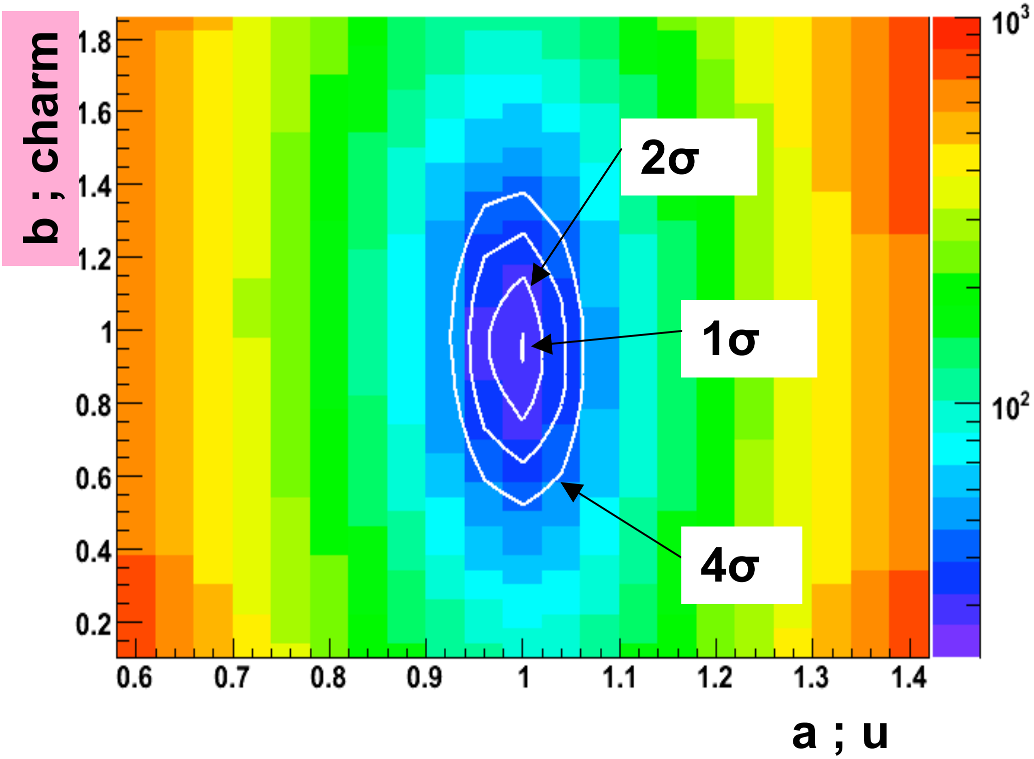
$$v_2^D(p_T) = a v_2^q\left(\frac{m_u}{m_D} p_T\right) + b v_2^q\left(\frac{m_c}{m_D} p_T\right) \rightarrow v_2^e$$

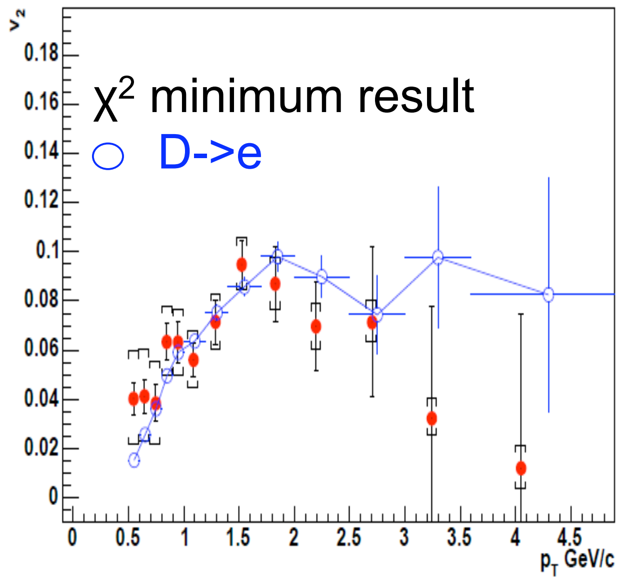
a,b ; fitting parameters

- simultaneous fit to $\mathbf{v_2^{\pi}}$, $\mathbf{v_2^{K}}$ and $\mathbf{v_2^{non\text{-}\gamma e}}$

Non-zero charm v_2 ? (2)

Shingo QM06





- χ^2 minimum ; a = 1, b = 0.96 (χ^2/ndf = 21.85/27)
- Based on this recombination model, the data suggest non-zero v_2 of charm quark.

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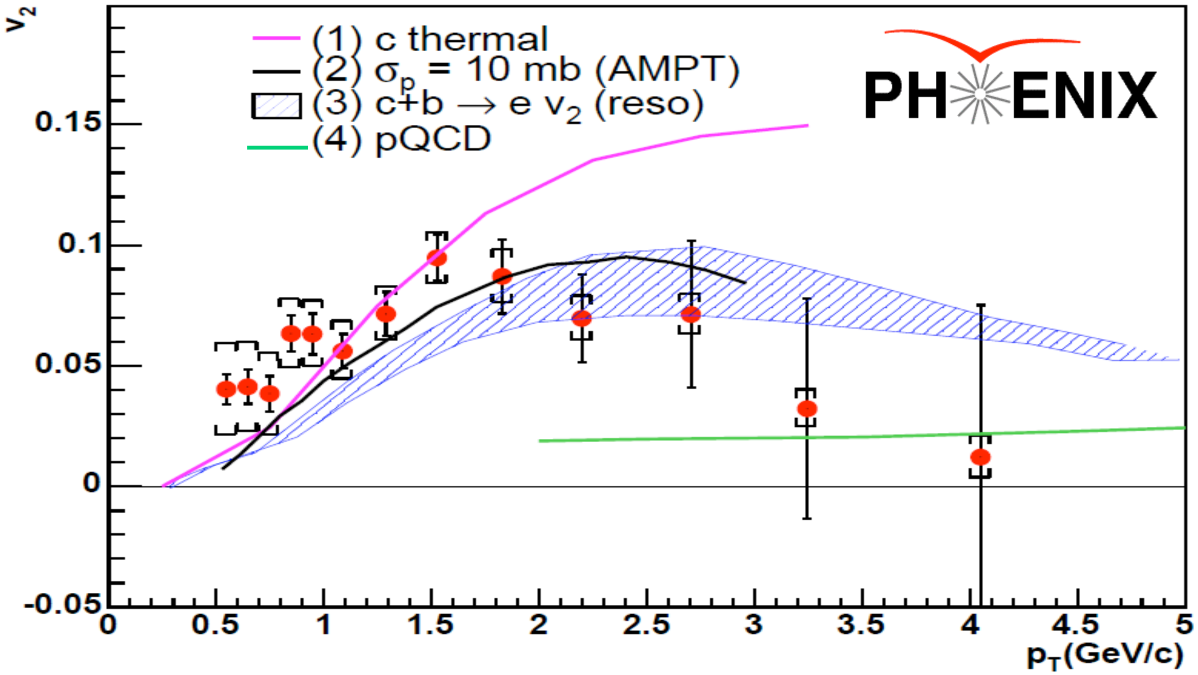
Compare with models



(1) Charm quark thermal + flow [Phys.Lett. B595 202-208]
(2) large cross section ; ~10 mb [PRC72,024906]
(3) Resonance state of D & B in sQGP [PRC73,034913]
(4) pQCD [PRB637,362]

Charm quark flows and Bottom seems to in higher pT
Charm/Bottom(pT) in the model

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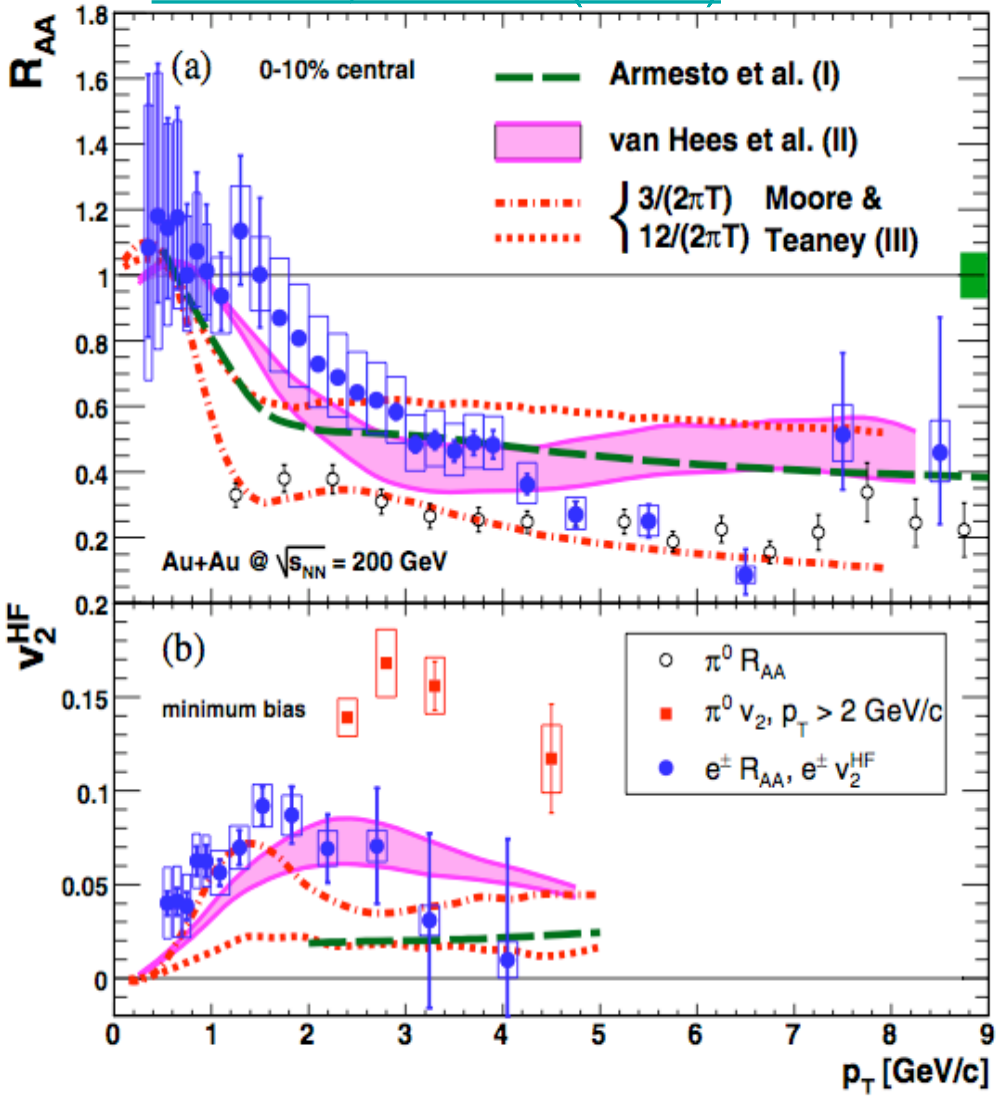
HQ Energy Loss and Flow

PRL. 98, 172301 (2007)



- Radiative energy loss only fails to reproduce v_2^{HF} ? + α[(2),(3)]
  On progress …….
  Djordjevic, Phys. Lett. B632 81 (2006)
  Armesto, Phys. Lett. B637 362 (2006
- Two models describes strong suppression and large v_2 simultaneously
  - Rapp and Van Hees
    Phys.Rev.C71:034907,2005
    - ✓ Elastic scattering : small τ
    - ✓ $D_{HQ} \times 2\pi T \sim 4 - 6$
  - Moore and Teaney
    Phys.Rev.C71:064904,2005
    - ✓ $D_{HQ} \times 2\pi T = 3\sim12$
- Recall $\varepsilon+p = T\,s$ at μ_B=0
  - This then gives **$\eta/s \sim(1.5\text{-}3)/4\pi$**
  - Within factor of 2 of conjectured bound
  Phys.Rev.D74,0850012,2006

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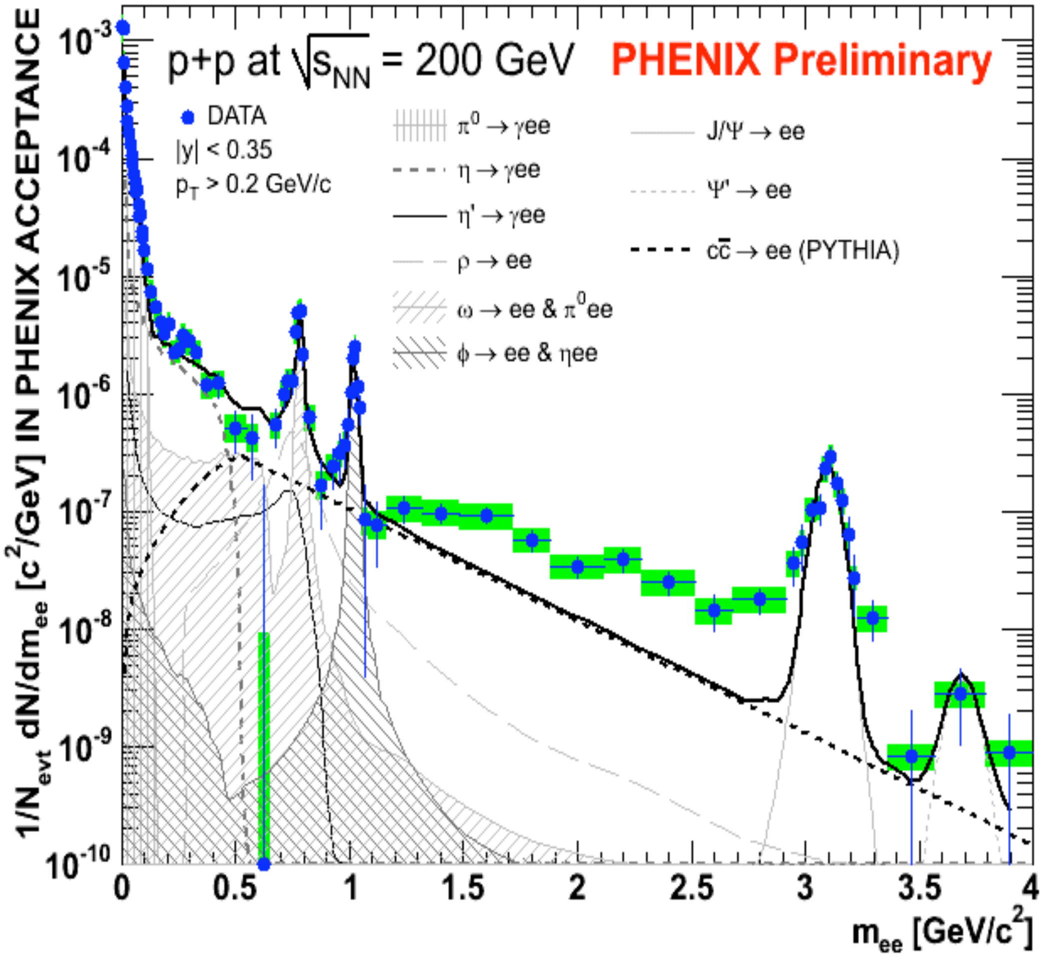
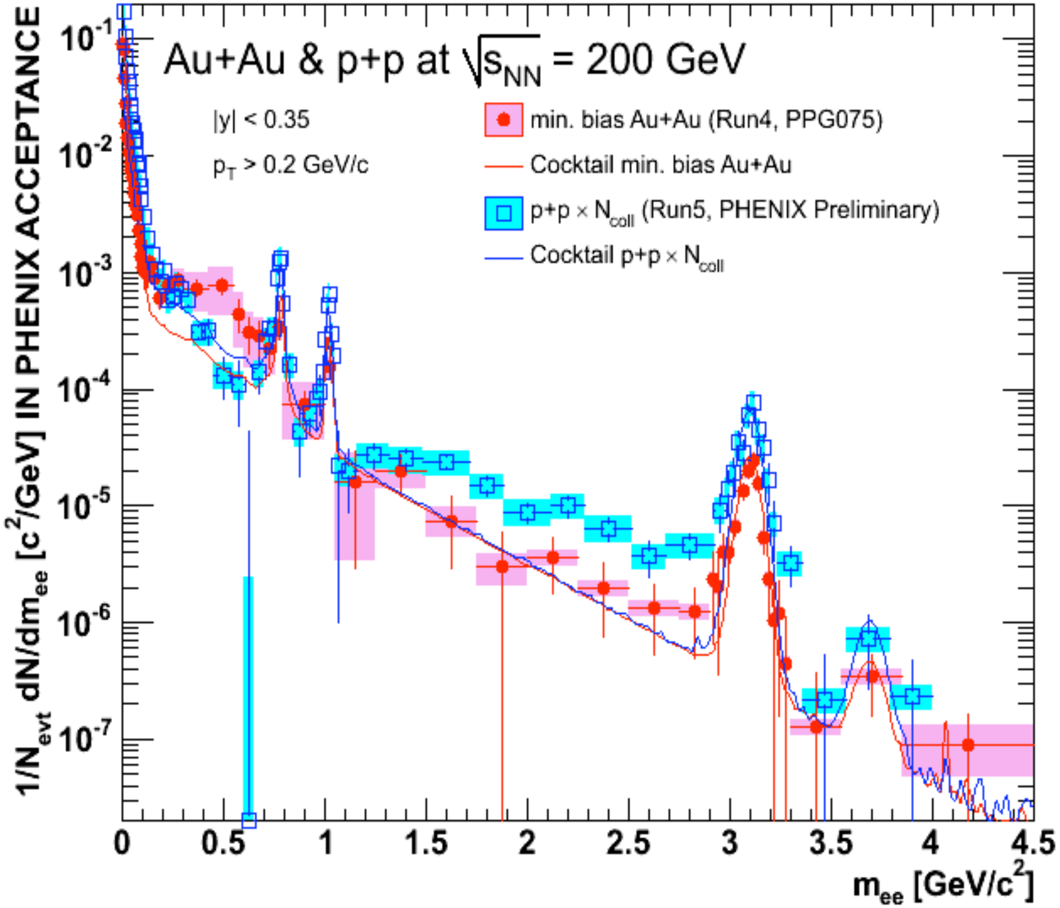
First Look at Continuum in p+p



- e^+e^- pair mass spectrum from Run 5 p+p
  - clearly indicates a signal in the range of m_{ee} > 1.5 GeV/c consistent with expectation from Open Charm correlated decays
  - PYTHIA under-predicts the data the same way as for the single lepton cross section
- Obtained an important reference for comparison with Au+Au results

Continuum in Au+Au

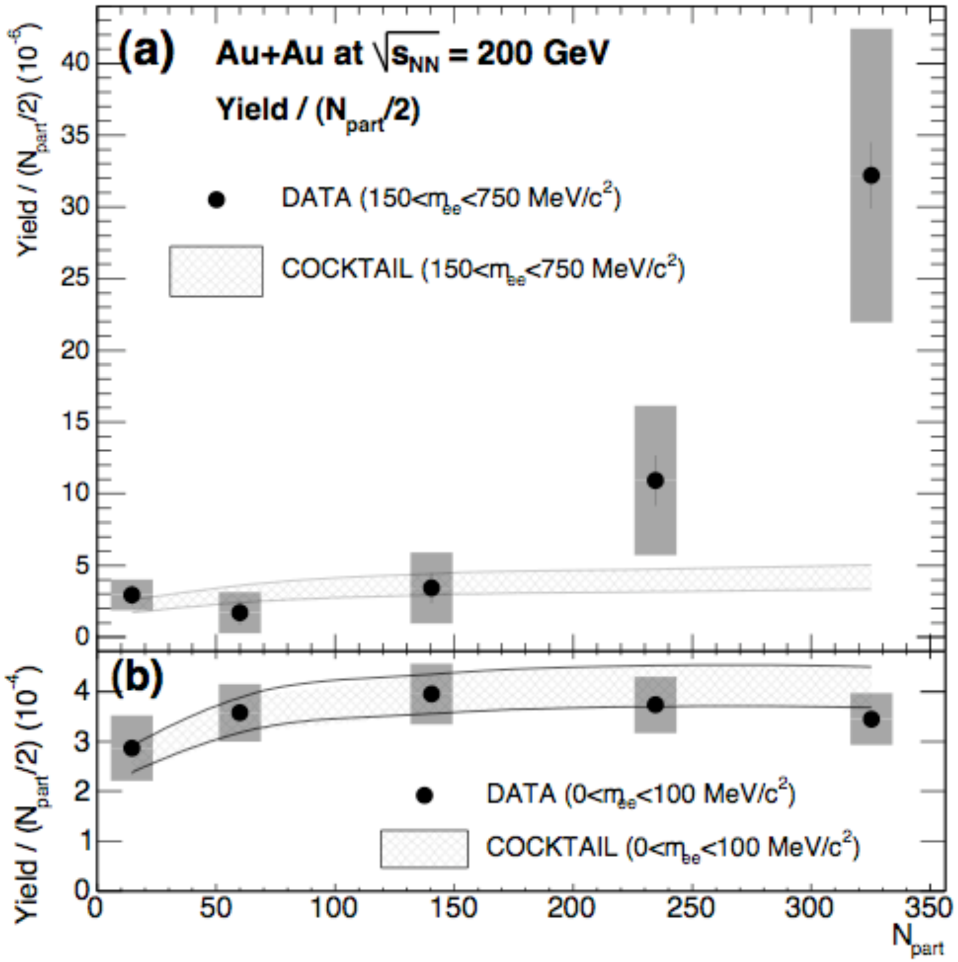


arXiv:0706.3034

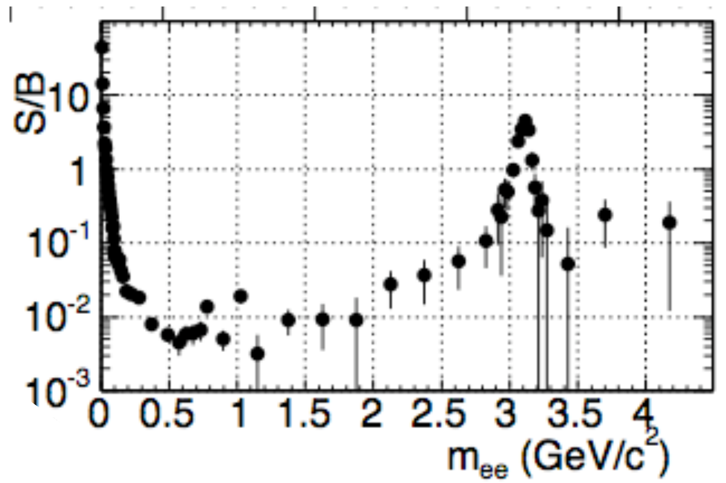
- p+p results, scaled by N_{coll} shows a suppression in region dominated by Open Charm
- Observe a sizable enhancement in low mass region

In-medium Enhancement of the dielectron continuum

arXiv:0706.3034



- Factor in most central DATA/COCKTAIL = 7.7 +- 0.6(stat.)+-2.5(syst.)+-1.5(model)



Summary(I)

pQCD jet quenching :

- One of the most celebrated results : issues
  - R_{AA} is of limited value for medium tomography
  - need better constraints on medium modeling : γ-h correlation
- Similar suppression pattern of high-p_T electrons from semi-leptonic *D* and *B* mesons decays as π^0; PRL 91, 172302 (2003) ;

1. how much elastic energy loss is playing a role ?
   - ✓ in addition to radiative energy loss ? $R_{AA}^{c-quark} \approx R_{AA}^{u,d}$
   - ✓ elastic energy loss is well known for π^0
2. α_s is playing a role on energy loss?
   - ✓ how much for radiative and elastic energy loss ?
     ($\Delta E^{radative} \propto \alpha^3_s$, $\Delta E^{elastic} \propto \alpha^2_s$)
   - ✓ α_s in the medium ? [A.Peshier hep-th/0605294]
3. how modeling of medium is well known?
   - ✓ Medium tomography: *T. Renk, K. Eskola* hep-ph/0610059
4. kT effect in the calculation is missing ?
5. Fragmentation and dissociation of hadrons from heavy quarks **inside the QGP** ? [**I. Vitev (A.Adil, I.V., hep-ph/0611109)**]

Summary(II)

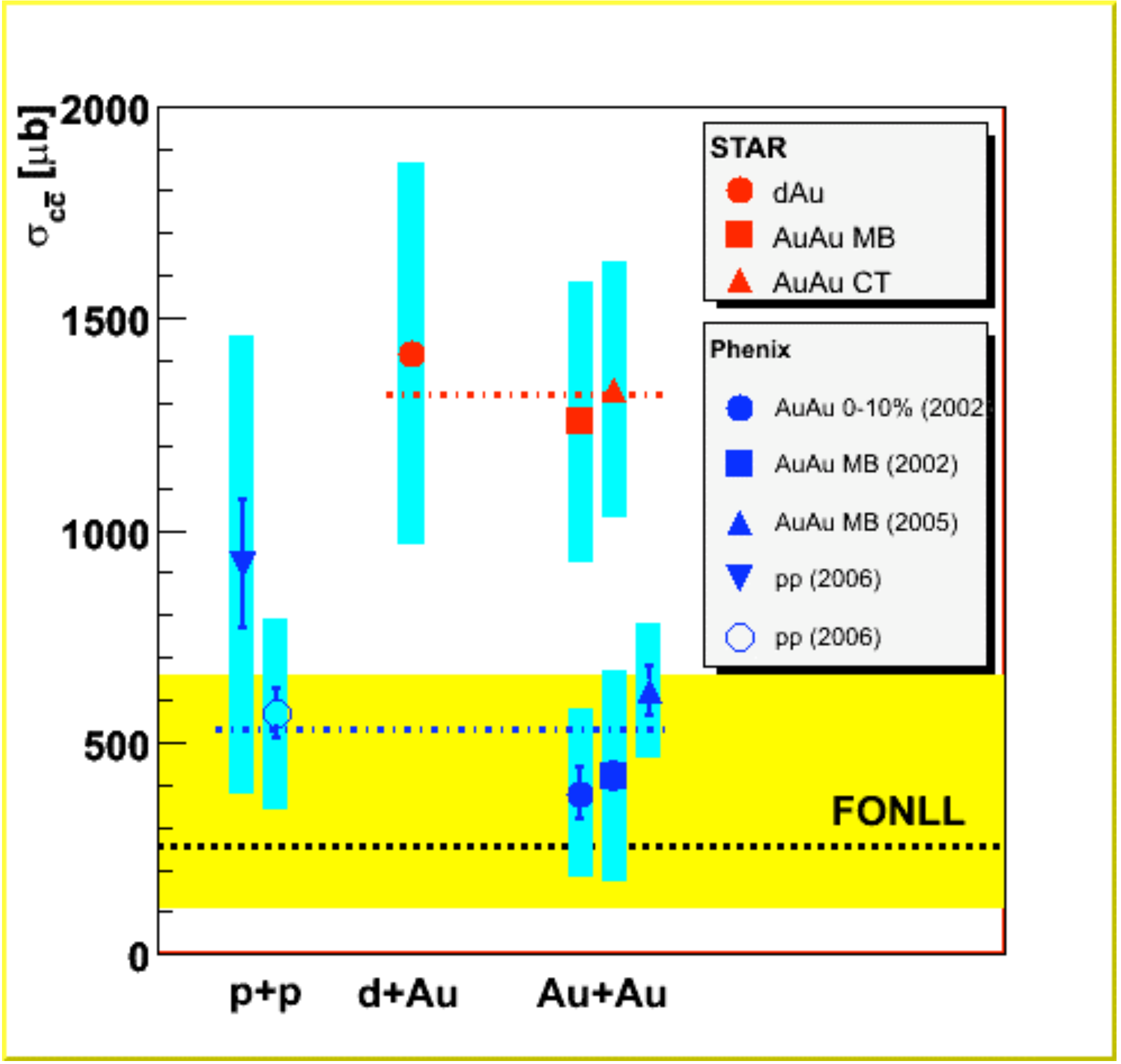
- Non-photonic electron R_{AA} & v_2 mainly from charm decay was measured @ √s = 200 GeV in Au+Au collisions at RHIC-PHENIX
  - Similar suppression as light quarks at high pT
  - non-zero v_2 is observed
- The data suggest non-zero v_2 of charm quark.
  - Charm quark strongly coupled to the matter
- Model comparison suggests
  - Small τ and/or D_{HQ} are required
  - η/s is very small, near quantum bound.
- First look at the continuum in p+p
- Better statistics [p+p(2006), Au+Au(2007)] + Better Reaction Plane Resolution will provide higher precision data soon.
- Hope for correlation study with larger statistics
- Direct measurement of Charm/Bottom with PHENIX upgrade
  - Direct measurement of Open Charm signal through hadronic D decay channels
  - Direct measurement of Open Bottom through J/ψ → B+X decay channel

Backup slides

- PHENIX vs STAR
- Eta/s

PHENIX

The difference also appears in Au+Au Collisions



Road to the solution in the near future:

•Direct D meson measurement from PHENIX.

•Low material run from STAR

The difference is cancelled out when calculate R_{AA}

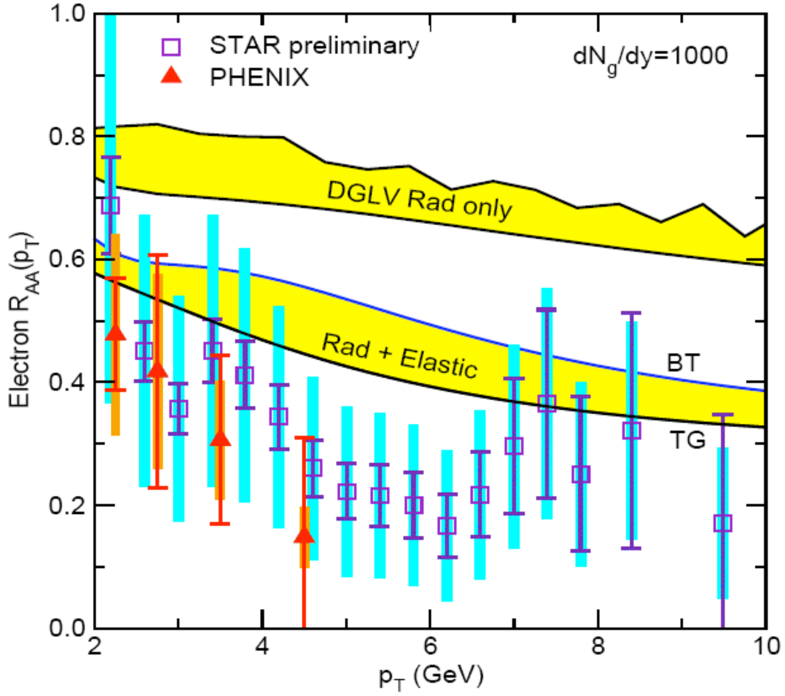
• The two experiment get consistent R_{AA} !!

JYVÄSKYLÄN YLIOPISTO
University of Jyväskylä

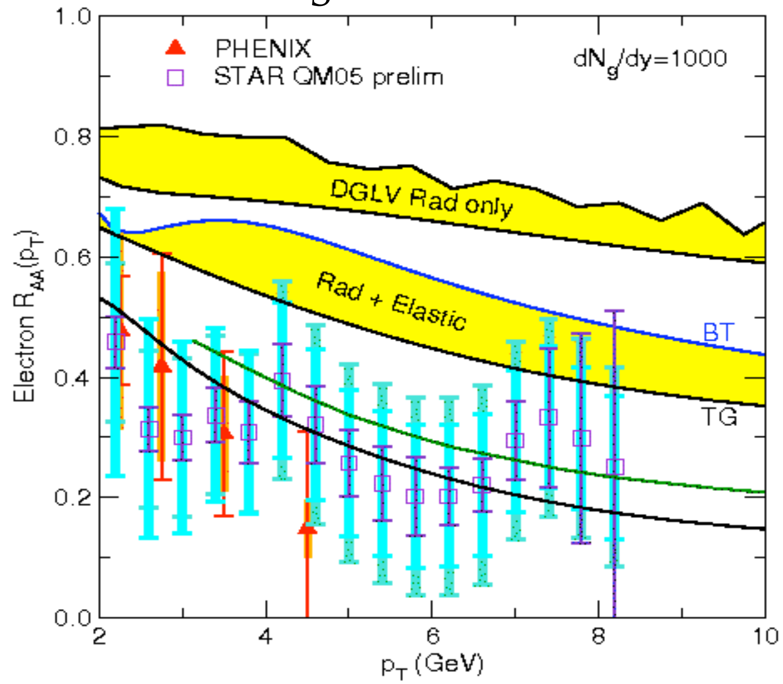
DongJo Kim, SQM07

With Different α_s

$\alpha_s = .3$



$\alpha_s = .4$

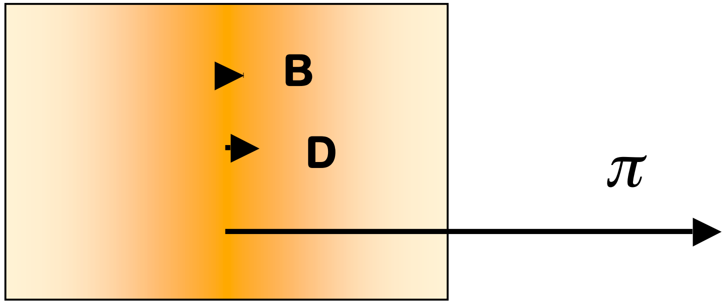


PHENIX

Collisional dissociation ?

I. Vitev (A.Adil, I.V., hep-ph/0611109)

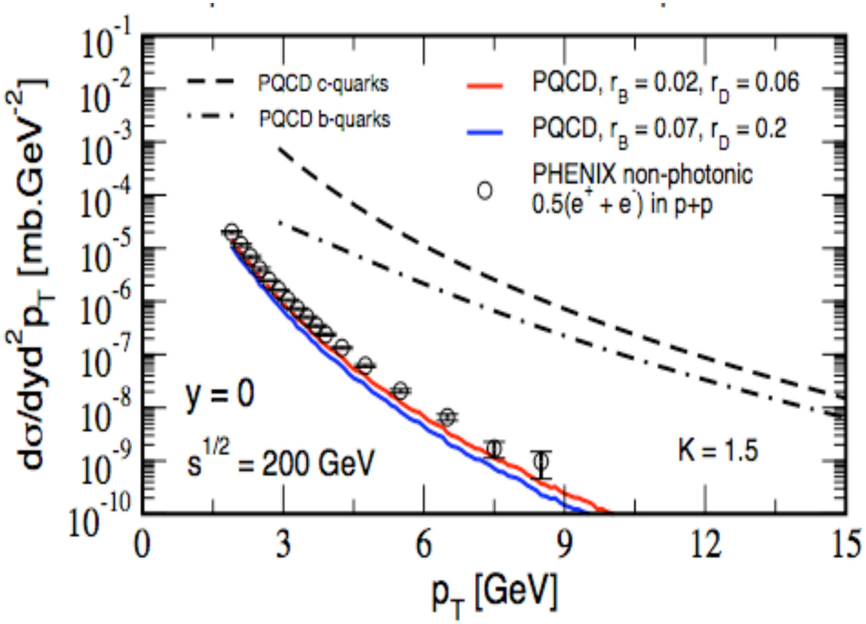
QGP extent

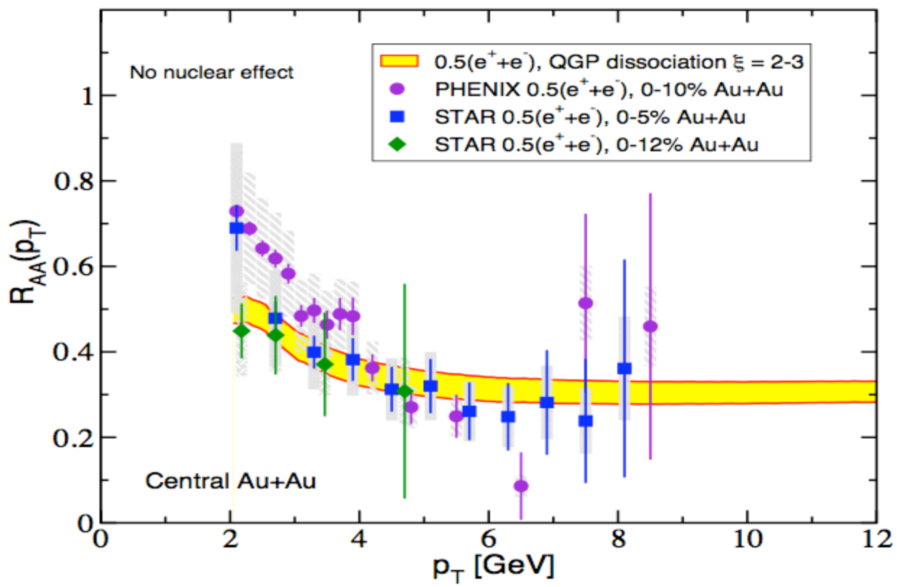


$$\tau_{\text{form}}(p_T = 10\ GeV)$$

	π	D	B
	25 fm	**1.6 fm**	**0.4 fm**

• Fragmentation and dissociation of hadrons from heavy quarks inside the QGP





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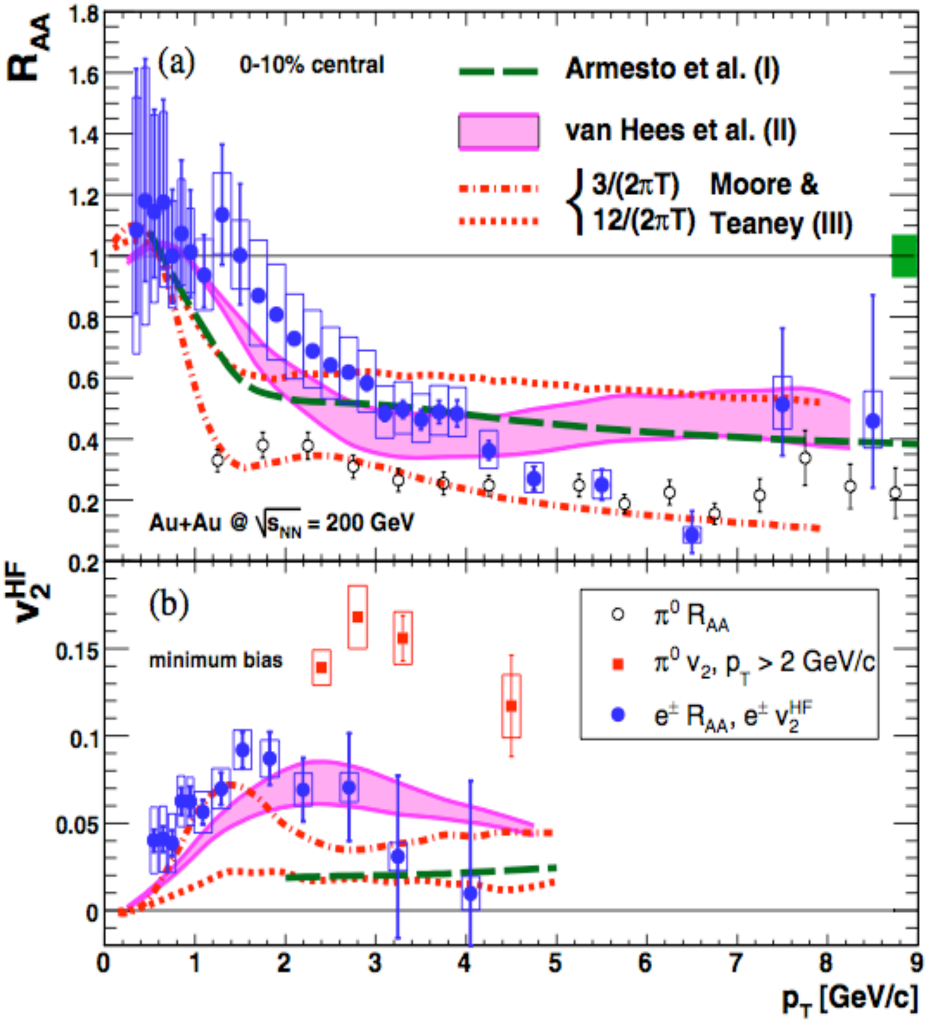

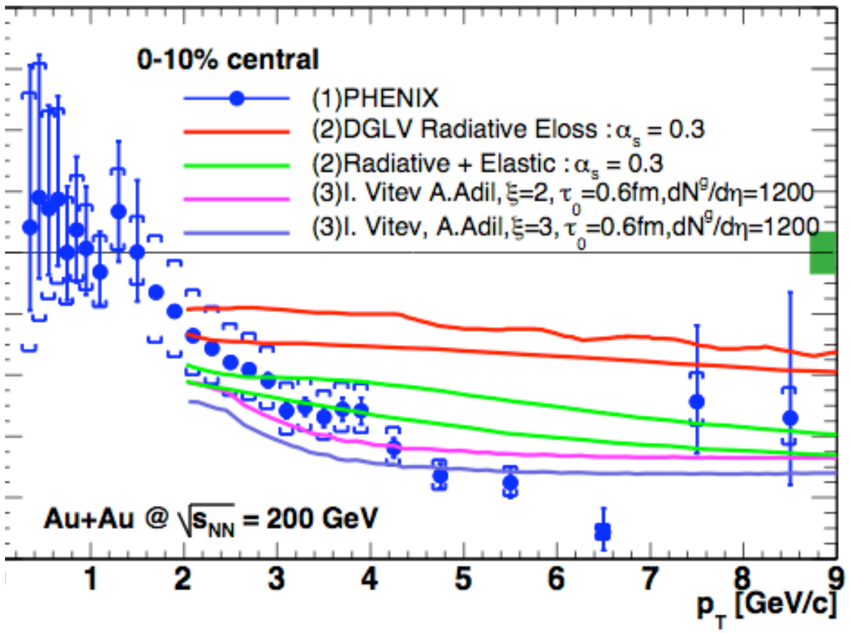

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